INSTITUTE OF AERONAUTICAL ENGINEERING

(Autonomous)

Dundigal, Hyderabad -500 043

ELECTRONICS AND COMMUNICATIONENGINEERING

COURSE LECTURE NOTES

Course Name	**OPTICAL COMMUNICATION**
Course Code	**AEC018**
Programme	B.Tech
Semester	VIII
Course Coordinator	Mr. U Soma Naidu , Assistant Professor
Course Faculty	Mr. U Soma Naidu , Assistant Professor
Lecture Numbers	1-45
Topic Covered	All

COURSE OBJECTIVES (COs):

The course should enable the students to:	
I	Understand the different kind of losses, signal distortion in optical wave guides and other signal degradation factors. Design optimization of SM fibers, RI profile and cut-off wave length.
II	Interpret various optical source materials, LED structures, quantum efficiency, Laser diodes and different fiber amplifiers.
III	Understand fiber optical receivers such as PIN APD diodes, noise performance in photo detector, receiver operation and configuration.
IV	Analyze fiber slicing and connectors, noise effects on system performance, operational principles WDM and solutions.

COURSE LEARNING OUTCOMES (CLOs):

Students, who complete the course, will have demonstrated the ability to do the following:

CLO Code	CLO's	At the end of the course, the student will have the ability to:	PO's Mapped	Strength of Mapping
AEC018.01	CLO 1	Understand Basic principles of optical fiber Communications.	PO 1, PO12	2
AEC018.02	CLO 2	Define light, propagation of light, modes, propagation of light different levels.	PO 1, PO 2 PO 4, PO 12	1
AEC018.03	CLO 3	Given the propagation of light in a cylindrical dielectric rod; rays and modes types of optical fibers.	PO 2	1

CLO Code	CLO's	At the end of the course, the student will have the ability to:	PO's Mapped	Strength of Mapping
AEC018.04	CLO 4	Given the Photonic components in optical communication systems .	PO 1, PO 2	2
AEC018.05	CLO 5	Understand modal analysis of a step index fiber, linearly polarized modes, single mode fibers and graded - index fiber.	PO 1	1
AEC018.06	CLO 6	Understand Signal Degradation And Optical Sources, Attenuation- Absorption, scattering losses, bending losses, core.	PO 1	1
AEC018.07	CLO 7	Explain cladding losses, optical waveguides; Material Dispersion, Waveguide Dispersion; Optical sources.	PO 1, PO 4	2
AEC018.08	CLO 8	Explain Semiconductor device fabrication, LED and LASER diode; Principles of operation, concepts of line width.	PO 1	2
AEC018.09	CLO 9	Understand phase noise, switching and modulation characteristics	PO 1, PO 2 PO 4, PO 12	1
AEC018.10	CLO 10	Define Optical detectors: pin detector, avalanche photodiode.	PO 4	2
AEC018.11	CLO 11	Understand Principles of operation, concepts of responsively, sensitivity and quantum efficiency, noise in detection.	PO 4	2
AEC018.12	CLO 12	Explain Multichannel Transmission Technique-Multichannel Frequency Modulation, Subcarrier multiplexing. WDM Concepts and Components.	PO 1, PO 4 PO 12	2
AEC018.13	CLO 13	Understand semiconductor amplifier, erbium-doped fiber amplifier, Raman amplifier, Brillouin amplifier.	PO 1, PO 4 PO 12	2
AEC018.14	CLO 14	Understand principles of operation, amplifier noise, signal to noise ratio, gain, gain bandwidth, gain.	PO 1, PO 4	2
AEC018.15	CLO 15	Explain noise dependencies, inter modulation effects, saturation induced crosstalk, wavelength range of operation.	PO 1, PO 12	2

CLO Code	CLO's	At the end of the course, the student will have the ability to:	PO's Mapped	Strength of Mapping
AEC018.16	CLO 16	Design Optical networks-SONET/SDH, ATM, IP, wavelength routed networks, soliton communication system.	PO 1	2
AEC018.17	CLO 17	Understand iber soliton, soliton based communication system design, high capacity and WDM soliton.	PO 1, PO 12	1

SYLLABUS

UNIT - I	OVERVIEW OF OPTICAL FIBRE COMMUNICATION	Classes: 10
OVERVIEW : Introduction to vector nature of light, propagation of light, propagation of light in a cylindrical dielectric rod; rays and modes; different types of optical fibers, modal analysis of a step index fiber, linearly polarized modes, single mode fibers and graded - index fiber.		
UNIT - II	**SIGNAL DEGRADATION AND OPTICAL SOURCES**	**Classes: 09**
Attenuation- Absorption, scattering losses, bending losses, core and cladding losses; signal distortion in optical waveguides; Material Dispersion, Waveguide Dispersion; Optical sources; Semiconductor device fabrication, LED and LASER diode; Principles of operation, concepts of line width, phase noise, switching and modulation characteristics.		
UNIT - III	**OPTICAL DETECTORS**	**Classes: 08**
Optical detectors: pin detector, avalanche photodiode - Principles of operation, concepts of responsively, sensitivity and quantum efficiency, noise in detection. Multichannel Transmission Technique-Multichannel Frequency Modulation, Subcarrier multiplexing. WDM Concepts and Components.		
UNIT - IV	**OPTICAL AMPLIFIERS**	**Classes: 08**
Basic concepts: semiconductor amplifier, erbium-doped fiber amplifier, Raman amplifier, Brillouin amplifier - principles of operation, amplifier noise, signal to noise ratio, gain, gain bandwidth, gain and noise dependencies, inter modulation effects, saturation induced crosstalk, wavelength range of operation.		
UNIT -V	**OPTICAL NETWORKS AND DISPERSION COMPENSATION**	**Classes: 10**
Optical networks: SONET/SDH, ATM, IP, wavelength routed networks, soliton communication system, fiber soliton, soliton based communication system design, high capacity and WDM soliton.		
Text Books:		
1. Keiser. G, "Optical fiber communications", Tata McGraw-Hill, 4th Edition, New Delhi, 2008. 2. Agrawal. G.P, "Fiber-Optic Communication Systems" John Wiley & Sons, 3rd Edition, 2002. 3.Emmanuel C, Ifeacher, Barrie. W. Jervis, DSP-A Practical Approach, Pearson Education, 2nd Edition, 2002.		

Reference Books:

1. John Gowar, “Optical Communication Systems”, Prentice Hall, 2nd Edition, 1993.
2. Franz, Jain, “Optical communication, Systems and Components”, Narosa Publications, 1st Edition New Delhi, 2000.
3. Karminvov, T. Li “Optical Fibre Telecommunications”, Vol A & B, Academic Press, 2002.

OVERVIEW OF OPTICAL FIBRE COMMUNICATION

Historical Development

- Fiber optics deals with study of propagation of light through transparent dielectric wageguides. The fiber optics are used for transmission of data from point to point location. Fiber optic systems currently used most extensively as the transmission line between terrestrial hardwired systems.

- The carrier frequencies used in conventional systems had the limitations in handlinmg the volume and rate of the data transmission. The greater the carrier frequency larger the available bandwith and information carrying capacity.

First generation

- The first generation of lightwave systems uses GaAs semiconductor laser and operating region was near 0.8 µm. Other specifications of this generation are as under:

i) Bit rate : 45 Mb/s

ii) Repeater spacing : 10 km

Second generation

i)	Bit rate	: 100 Mb/s to 1.7 Gb/s
ii)	Repeater spacing	: 50 km
iii)	Operation wavelength	: 1.3 µm
iv)	Semiconductor	: In GaAsP

Third generation

i)	Bit rate	: 10 Gb/s
ii)	Repeater spacing	: 100 km
iii)	Operating wavelength	: 1.55 µm

Fourth generation

Fourth generation uses WDM technique.

Bit rate : 10 Tb/s

Repeater spacing : > 10,000 km

Operating wavelength : 1.45 to 1.62 µm

Fifth generation

Fifth generation uses Roman amplification technique and optical solitiors.

Bit rate : 40 - 160 Gb/s

Repeater spacing : 24000 km - 35000 km

Operating wavelength : 1.53 to 1.57 µm

Need of fiber optic communication

- Fiber optic communication system has emerged as most important communication system. Compared to traditional system because of following requirements :
    1. In long haul transmission system there is need of low loss transmission medium
    2. There is need of compact and least weight transmitters and receivers.
    3. There is need of increase dspan of transmission.
    4. There is need of increased bit rate-distrance product.
- A fiber optic communication system fulfills these requirements, hence most widely acception.

General Optical Fiber Communication System

- Basic block diagram of optical fiber communication system consists of following important blocks.
    1. Transmitter
    2. Information channel
    3. Receiver.

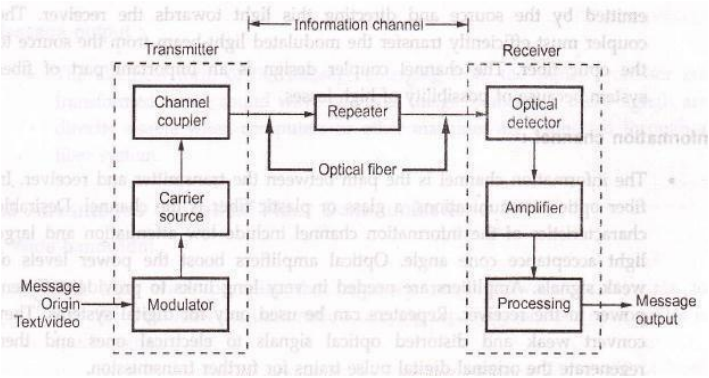


Fig. 1.2.1 shows block diagram of OFC system.

Message origin :

- Generally message origin is from a transducer that converts a non-electrical message into an electrical signal. Common examples include microphones for converting sound waves into currents and video (TV) cameras for converting images into current. For data transfer between computers, the message is already in electrical form.

Modulator :

- The modulator has two main functions.

  1) It converts the electrical message into the proper format.

  2) It impresses this signal onto the wave generated by the carrier source.

  Two distinct categories of modulation are used i.e. analog modulation and digital modulation.

Carrier source :

- Carrier source generates the wave on which the information is transmitted. This wave is called the carrier. For fiber optic system, a laser diode (LD) or a light emitting diode (LED) is used. They can be called as optic oscillators, they provide stable, single frequency waves with sufficient power for long distance propagation.

Channel coupler :

- Coupler feeds the power into the information channel. For an atmospheric optic system, the channel coupler is a lens used for collimating the light emitted by the source and directing this light towards the receiver. The coupler must efficiently transfer the modulated light beam from the source to the optic fiber. The channel coupler design is an important part of fiber system because of possibility of high losses.

Information channel :

- The information channel is the path between the transmitter and receiver. In fiber optic communications, a glass or plastic fiber is the channel. Desirable characteristics of the information channel include low attenuation and large light acceptance cone angle. Optical amplifiers boost the power levels of weak signals. Amplifiers are needed in very long links to provide sufficient power to the receiver. Repeaters can be used only for digital systems. They convert weak and distorted optical signals to electrical ones and then regenerate the original disgital pulse trains for further transmission.

- Another important property of the information channel is the propagation time of the waes travelling along it. A signal propagating along a fiber normally contains a range of optic frequencies and divides its power along several ray paths. This results in a distortion of the propagating signal. In a digital system, this distortion appears as a spreading and deforming of the pulses. The spreading is so great that adjacent pulses begin to overlap and become unrecognizable as separate bits of information.

Optical detector :

- The information being transmitted is detector. In the fiber system the optic wave is converted into an electric current by a photodetector. The current developed by the

- detector is proportional to the power in the incident optic wave. Detector output current contains the transmitted information. This detector output is then filtered to remove the constant bias and thn amplified.

- The important properties of photodetectors are small size, economy, long life, low power consumption, high sensitivity to optic signals and fast response to quick variations in the optic power.

Signal processing :

- Signal processing includes filtering, amplification. Proper filtering maximizes the ratio of signal to unwanted power. For a digital system decision circuit is an additional block. The bit error rate (BER) should be very small for quality communications.

Message output :

- The electrical form of the message emerging from the signal processor are transformed into a soud wave or visual image. Sometimes these signals are directly usable when computers or other machines are connected through a fiber system.

Advantages of Optical Fiber Communications

1. Wide bandwidth

- The light wave occupies the frequency range between 2 x 1012 Hz to 3.7 x 1012 Hz. Thus the information carrying capability of fiber optic cables is much higher.

2. Low losses

- Fiber optic cables offers bery less signal attenuation over long distances. Typically it is less than 1 dB/km. This enables longer distance between repeaters.

3. Immune to cross talk

- Fiber optic cables has very high immunity to electricaland magnetic field. Since fiber optic cables are non-conductors of electricity hence they do not produce magnetic field. Thus fiber optic cables are immune to cross talk between cables cause dby magnetic induction.

4. Interference immune

- Fiber optic cable sar eimmune to conductive and radiative interferences caused by electrical noise sources such as lighting, electric motors, fluorescent lights.

5. Light weight

- As fiber cables are made of silica glass or plastic which is much lighter than copper or aluminium cables. Light weight fiber cables are cheaper to transport.

6. Small size

- The diameter of fiber is much smaller compared to other cables, therefore fiber calbe is small in size, requires less storage space.

7. More strength

- Fiber cables are stronger and rugged hence can support more weight.

8. Security

- Fiber cables are more secure than other cables. It is almost impossible to tap into a fiber cable as they do n ot radiate signals.

No ground loops exist between optical fibers hence they are more secure.

9. Long distance transmission

- Becaujse of less attenuation transmission at a longer distance is possible.

10. Environment immune

- Fiber calbes are more immune to environmental extremes. They can operate over a large temperature varioations. Also they are not affected bycorrosive liquids and gases.

11. Sage and easy installation

- Fiber cables are safer and easier to install and maintain. They are non-conductors hence there is no shock hazards as no current or voltage is associated with them. Their small size and light weight feature makes installation easier.

12. Less cost

- Cost of fiber optic system is less compated to any other system.

Disadvantages of Optical Fiber Communicaitons

1. High initial cost

- The intial cost of installation or setting up cost is very high compared to all other system.

2. Maintenance and repaiding cost

- The maintenance and repaiding of fiber optic systems is not only difficult but expensive also.

3. Jointing and test procedures

- Since optical fibers are of very small size. The fiber joining process is very constly and requires skilled manpower.

4. Tensile stress

- Optical fibers are more susceptible to buckling, bending and tensile stress than copper cables. This leades to restricted practice to use optical fiber technology to premises and floor backbones with a few interfaces to the copper cables.

5. Short links

- Eventhough optical fiber calbes are inexpensive, it is still not cost effective to replace every small conventional connector (e.g. between computers and peripherals), as the price of optoelectronic transducers are very high.

6. Fiber losses

- The amount of optical fiber available to the photodetector at the end of fiber length depends on various fiber losses such as scattering, dispersion, attenuation and reflection.

Applications of Optical Fiber Communicaitons

- Applications of optical fiber communications include telecommunications, data communications, video control and protection switching, sensors and power applications.

1. Telephone networks

- Optical waveguide has low attenuation, high transmission bandwidth compated to copper lines, therefore numbers of long haul co-axial trunks l;links between telephone exchanges are being replaced by optical fiber links.

2. Urban broadband service networks

- Optical waveguide provides much larger bandwidth than co-axial calbe, also the number of repeaters required is reduced considerably.

- Modern suburban communications involves videotext, videoconferencing videotelephony, switched broadband communication network. All these can be supplied over a single fiber optic link. Fiber optic calbes is the solution to many of today's high speed, high bandwidth data communication problems and will continue to play a large role in future telecom and data-com networks.

Optical Fiber Waveguides

- In free space light ravels as its maximum possible speed i.e. 3 x 10^8 m/s or 186 x 10^3 miles/sec. When light travels through a material it exnibits certain behavior explaned by laws of reflection, refraction.

Electromagnetic Spectrum

- The radio waves and light are electromagnetic waves. The rate at which they alternate in polarity is called their frequency (f) measured in hertz (Hz). The speed of electromagnetic wave (c) in free space is approximately 3 x 10^8 m/sec. The distance travelled during each cycle is called as wavelength (λ)

$$\text{Wavelength } (\lambda) = \frac{\text{Speed of light}}{\text{Frequency}} = \frac{c}{f}$$

- In fiber optics, it is more convenient to use the wavelength of light instead of the frequency with light frequencies, wavlengfth is often stated in microns or nanometers.

  1 micron (μ) = 1

  Micrometre (1 x 10^{-6}) 1

  nano (n) = 10^{-9} metre

- Fiber optics uses visible and infrared light. Infrared light covers a fairly wide range of wavelengths and is generally used for all fiber optic communications. Visible light is normally used for very short range transmission using a plastic fiber.

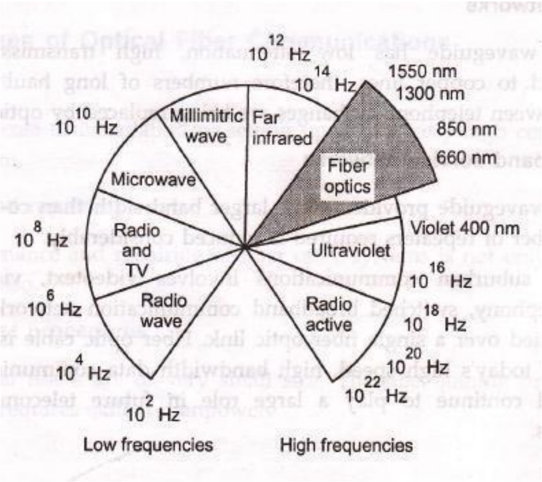


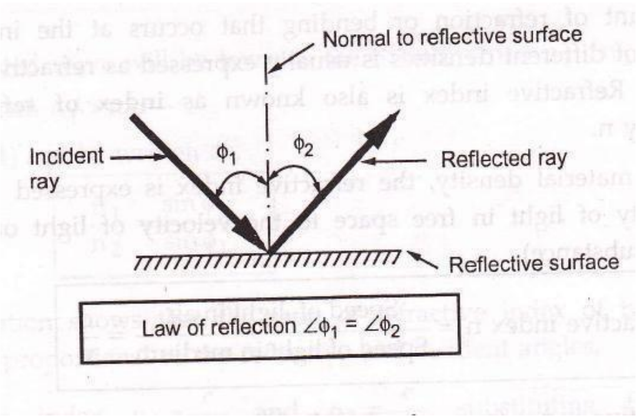
Fig. 1.6.1 shows electromagnetic frequency spectrum

Ray Transmission Theory

- Before studying how the light actually propagates through the fiber, laws governing the nature of light m ust be studied. These was called as **laws of optics (Ray theory).** There is conception that light always travels at the same speed. This fact is simply not true. The speed of light depends upon the material or medium through which it is moving. In free space light travels at its maximum possible speed i.e. 3 x 108 m/s or 186 x 103 miles/sec. When light travels through a material it exhibits certain behavior explained by laws of reflection, refraction.

Reflection

- The law of reflection states that, when a light ray is incident upon a reflective surface at some incident angle ϕ_1 from imaginary perpendicular normal, the ray will be reflected from the surface at some angle ϕ_2 from normal which is equal to the angle of incidence.



Refraction

- Refraction occurs when light ray passes from one medium to another i.e. the light ray changes its direction at interface. Refraction occurs whenever density of medium changes. E.g. refraction occurs at air and water interface, the straw in a glass of water will appear as it is bent.

The refraction can also observed at air and glass interface.

- When wave passes through less dense medium to more dense medium, the wave is refracted (bent) towards the normal. Fig. 1.6.3 shows the refraction phenomena.

- The refraction (bending) takes place because light travels at different speed in different mediums. The speed of light in free space is higher than in water or glass.

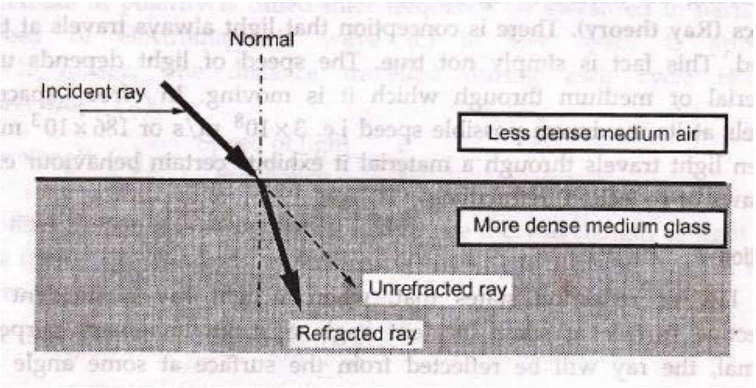


Fig.1.6.3 Refraction

Refractive Index

- The amount of refraction or bending that occurs at the interface of two materials of different densities is usually expressed as refractive index of two materials. Refractive index is also known as **index of refraction** and is denoted by n.

- Based on material density, the refractive index is expressed as the ratio of the velocity of light in free space to the velocity of light of the dielectric material (substance).

$$\boxed{\text{Refractive index } n = \frac{\text{Speed of light in air}}{\text{Speed of light in medium}} = \frac{c}{v}}$$

The refractive index for vacuum and air os 1.0 for water it is 1.3 and for glass refractive index is 1.5.

Snell's Law

- Snell's law states how light ray reacts when it meets the interface of two media having different indexes of refraction.

- Let the two medias have refractive indexes n1 and n2 where n1 >n2.

  ϕ1 and ϕ2 be the angles of incidence and angle of refraction respectively.

Then according to Snell's law, a relationship exists between the refractive index of both materials given by

$$n1 \sin\phi1 = n2 \sin\phi2 \qquad \ldots (1.6.1)$$

- A refractive index model for Snell's law is shown in Fig. 1.6.4.

- The refracted wave will be towards the normal when $n_1 < n_2$ and will away from it when $n_1 > n_2$.

Equation (1.6.1) can be written as,

$$\boxed{\frac{n_1}{n_2} = \frac{\sin \phi_2}{\sin \phi_1}}$$

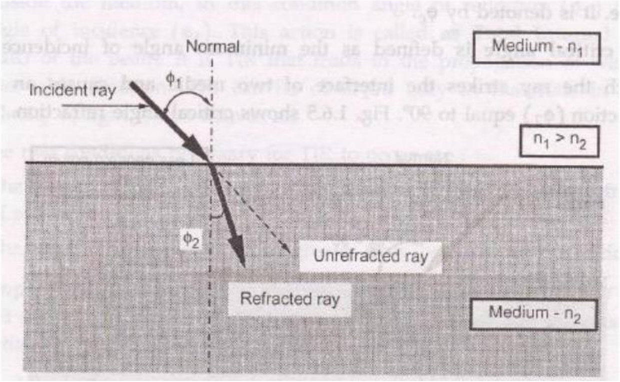


Fig 1.6.4 Refractive model for Snells Law

- This equation shows that the ratio of refractive index of two mediums is inversely proportional to the refractive and incident angles.

As refractive index $n_1 = \frac{c}{v_1}$ and $n_2 = \frac{c}{v_2}$ substituting these values in equation (1.6.2)

$$\frac{c / v_1}{c / v_2} = \frac{\sin \phi_2}{\sin \phi_1}$$

$$\frac{v_2}{v_1} = \frac{\sin \phi_2}{\sin \phi_1}$$

Critical Angle

- When the angle of incidence (ϕ_1) is profressively increased, there will be progressive increase of refractive angle (ϕ_2). At some condition (ϕ_1) the refractive angle (ϕ_2) becomes 90o to the normal. When this happens the refracted light ray travels along the interface. The angle of incidence (ϕ_1) at the point at which the refractive angle (ϕ_1) becomes 90^{O} is called the critical angle. It is denoted by ϕ_c.

- The **critical angle** is defined as the minimum angle of incidence (ϕ_1) at which the ray strikes the interface of two media and causes an agnle of refraction (ϕ_2) equal to 90^{O}. Fig 1.6.5 shows critical angle refraction.

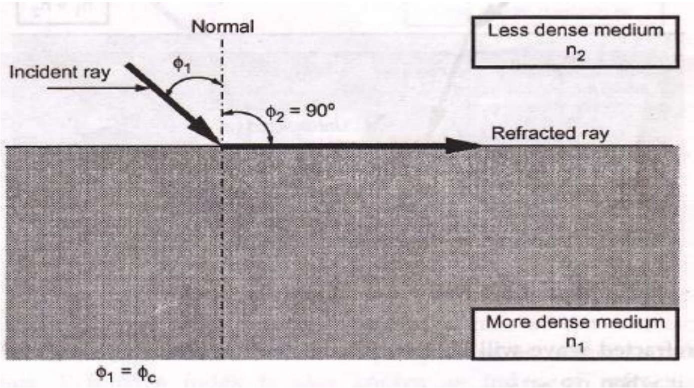


Fig.1.6.5 Critical Angle

Hence at critical angle $\phi_1 = \phi_c$ and $\phi_2 = 90^{o}$ Using

Snell's law : $n_1 \sin \phi_1 = n_2 \sin \phi_2$

$$\sin \phi_c = \frac{n_2}{n_1} \sin 90^o$$

$$\because \quad \sin 90° = 1$$

$$\sin \phi_c = \frac{n_2}{n_1}$$

Therefore,

$$\boxed{\text{Critical angle } \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)}$$

... (1.6.3)

- The actual value of critical angle is dependent upon combination of materials present on each side of boundary.

Total Internal Refleciton (TIR)

- When the incident angle is increase dbeyond the critical angle, the light ray does not pass through the interface into the other medium. This gives the effect of mirror exist at the interface with no possibility of light escaping outside the medium. In this condition angle of reflection ($\phi 2$) is equal to angle of incidence ($\phi 1$). This action is called as **Total Internal Reflection (TIR)** of the beam. It is TIR that leads to the propagation of waves within fiber-cable medium. TIR can be observed only in materials in which the velocity of light is less than in air.

The refractive index of first medium must be greater than the refractive index of second one.

1. The angle of incidence must be greater than (or equal to) the critical angle.

Example 1.6.1 : A light ray is incident from medium-1 to medium-2. If the refractive indices of medium-1 and medium-2 are 1.5 and 1.36 respectively then determine the angle of refraction for an angle of incidence of 30^{o}.

Solution : Medium-1 n1 = 1.5

Medium-2 n2 = 1.36

Angle of incidence $\phi 1 = 30^{o}$.

Angle of incident $\phi 2$ = ?

$$\boxed{\text{Snell'slaw}: n_1 \sin\phi_1 = n_2 \sin\phi_2}$$

$$1.5 \sin 30^{\circ} = 1.36 \sin\phi_2$$

$$\sin\phi_2 = \frac{1.5}{1.36} \sin 30^{\circ}$$

$$\sin\phi_2 = 0.55147$$

$$\therefore \qquad \phi_2 = 33.46^{\circ}$$

Angle of refraction 33.46^{o} from normal. **… Ans.**

Example 1.6.2 : A light ray is incident from glass to air. Calculate the critical angle (ϕ_c).

Solution : Refractive index of glass n_1 = 1.50

Refrative indes of air n_2 = 1.00

$$\boxed{\text{Snell's law}: n_1 \sin\phi_1 = n_2 \sin\phi_2}$$

$$\sin\phi_1 = \frac{n_2}{n_1}\sin\phi_2$$

$$\therefore \qquad \sin\phi_1 = \frac{n_2}{n_1}\sin 90^\circ$$

Example 1.6.3 : Calculate the NA, acceptance angle and critical angle of the fiber having n_1 (Core refractive index) = 1.50 and refractive index of cladding = 1.45.

Soluiton : n_1 = 1.50, n_2 = 1.45

$$\Delta = \frac{(n_1 - n_2)}{(n_1)} = \frac{1.50 - 1.45}{1.50} = 0.033$$

$$\text{Numerical aperture, NA} = n_1\sqrt{2\Delta}$$

$$\text{NA} = 1.50\sqrt{2 \times 0.033}$$

$$\text{NA} = 0.387$$

$$\text{Acceptance angle } \phi_0 = \sin^{-1}\text{NA} \qquad \phi_0 = \sin^{-1} 0.387$$

$$\text{Critical angle } \phi_c = \sin^{-1}\frac{n_2}{n_1} \qquad \phi_c = \sin^{-1}\frac{1.45}{1.50}$$

$$\phi_0 = 22.78^\circ$$

Optical Fiver as Waveguide

- An optical fiber is a cylindrical dielectric waveguide capable of conveying electromagnetic waves at optical frequencies. The electromagnetic energy is in the form of the light and propagates along the axis of the fiber. The structural of the fiver determines the transmission characteristics.
- The propagation of light along the waveguide is decided by the modes of the waveguides, here mode means path. Each mode has distict pattern of electric and magnetic field distributions along the fiber length. Only few modes can satisfy the homogeneous wav equation in the fiver also the boundary condition a waveguide surfaces. When there is only one path for light to follow then it is called as single mode propagation. When there is more than one path then it is called as multimode propagation.

Single fiber structure

- A single fiber structure is shown in Fig. 1.6.6. It consists of a solid dielectric cylinder with radius ‘a’. This cylinder is called as **core** of fiber. The core is surrounded by dielectric, called **cladding**. The index of refraction of core (glass fiber) is slightly greater than the index of refraction of cladding.

If refractive index of core (glass fiver) = n_1 and

refractive index of cladding = n_2

then $n_1 > n_2$.

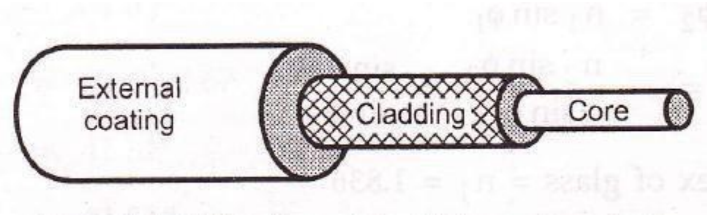


Fig.1.6.6. Single optical Fibre Structure

Propagation in Optical Fiber

- To understand the general nature of light wave propagation in optical fiber. We first consider the construction of optical fiber. The innermost is the glass core of very thin diameter with a slight lower refractive index n2. The light wave can propagate along such a optical fiber. A single mode propagation is illustrated in Fig. 1.6.7 along with standard size of fiber.

Single mode fibers are capable of carrying only one signal of a specific wavelength.

- In multimode propagation the light propagates along the fiber in zigzag fashion, provided it can undergo total internal reflection (TIR) at the core cladding boundaries.
- Total internal reflection at the fiber wall can occur only if two conditions are satisfied.

Condition 1:

The index of refraction of glass fiber must be slightly greater than the index of refraction of material surrounding the fiber (cladding).

If refractive index of glass fiber = n_1

and refractive index of cladding = n_2

then $n_1 > n_2$.

Condition 2 :

The angle of incidence (ϕ_1) of light ray must be greater than critical angle (ϕ_c).

- A light beam is focused at one end of cable. The light enters the fibers at different angles.

  Fig. 1.6.8 shows the conditions exist at the launching end of optic fiber. The light source is surrounded by air and the refractive index of air is $n_0 = 1$. Let the incident ray makes an angle ϕ_0 with fiber axis. The ray enters into glass

  fiber at point P making refracted angle ϕ_1 to the fiber axis, the ray is then propagated diagonally down the core and reflect from the core wall at point

  Q. When the light ray reflects off the inner surface, the angle of incidence is equal to the angle of reflection, which is greater than critical angle.

- In order for a ray of light to propagate down the cable, it must strike the core cladding interface at an angle that is greater than critical angle (ϕ_c).

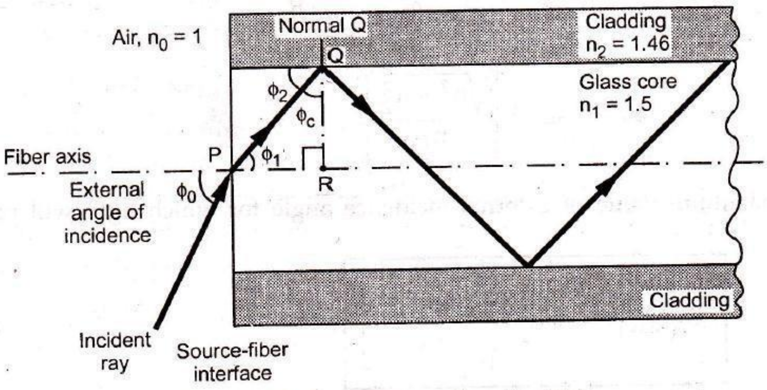


Fig. 1.6.8 Ray propagation by TIR

Acceptance Angle

Applying Snell's law to external incidence angle.

$$n_0 \sin \phi_0 = n_1 \sin \phi_1$$

But $$\phi_1 = (90 - \phi_c)$$

$$\sin \phi_1 = \text{sing } (90 - \phi_c) = \cos \phi_c$$

$$\cos \phi = \sqrt{n_1^2 - n_2^2}$$

Substituting sin ϕ_1 in above equation.

$$n_0 \sin \phi_0 = n_1 \cos \phi_c$$

$$\sin \phi_c = \frac{n_1}{n_0} \cos \phi_c$$

Applying Pythagorean theorem to ΔPQR.

The maximum value of external incidence angle for which light will propagate in the fiber.

$$\boxed{\phi_{0(\max)} = \sin^{-1}\left[\frac{\sqrt{n_1^2 - n_2^2}}{n_0}\right]}$$

When the light rays enters the fivers from an air medium $n_0 = 1$. Then above equation reduces to,

$$\phi_{0(\max)} = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$$

The angle ϕ_0 is called as **acceptance angle** and $\phi_{0(\max)}$ defines the maximum angle in which the light ray may incident on fiber to propagate down the fiber.

Acceptance Cone

- Rotating the acceptance angle $\phi_{0(\max)}$ around the fiber axis, a cone shaped pattern is obtained, it is called as **acceptance cone** of the fiber input. Fig 1.6.10 shows formation of acceptance cone of a fiber cable.

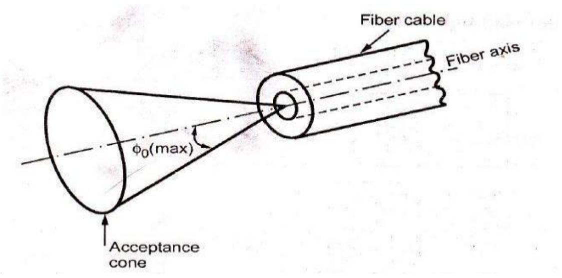


FIG: 1.6.10 shows formation of acceptance cone of a fiber cable.

- The Cone of acceptance is the angle within which the light is accepted into the core and is able to travel along the fiber. The launching of light wave becomes easier for large acceptance come.
- The angle is measured from the axis of the positive cone so the total angle of convergence is actually twice the stated value.

Numerical Aperture (NA)

- The **numerical aperture** (NA) of a fiber is a figure of merit which represents its light gathering capability. Larger the numerical aperture, the greater the

  amount of light accepted by fiber. The acceptance angle also determines how much light is able to be enter the fiber and hence there is relation between the numerical aperture and the cone of acceptance.

Numerical aperture (NA) = $\sin \phi_{0(max)}$

$$NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

For air $n_0 = 1$

∴

$$NA = \sqrt{n_1^2 - n_2^2}$$

$$\boxed{NA = \sqrt{n_{core}^2 - n_{cladding}^2}}$$

Hence acceptance angle = $\sin^{-1}$ NA

By the formula of NA note that the numerical aperture is effectively dependent only on refractive indices of core and cladding material. NA is not a function of fiber dimension.

- The index difference (Δ) and the numerical aperture (NA) are related to the core and cladding indices:

Example 1.6.5 : Calculate the numerical aperture and acceptance angle for a fiber cable of which $n_{core} = 1.5$ and $n_{cladding} = 1.48$. The launching takes place from air. … (1.6 .4)

Solution: $NA = (n_1^2 - n_2^2)^{1/2}$

$$NA = \sqrt{n_{core}^2 - n_{cladding}^2}$$

$$NA = n_1 (2\Delta)^{1/2}$$

$$NA = \sqrt{1.5^2 - 1.48^2}$$

NA = **0.244** **…Ans.**

Acceptance angle –

$$\sin^{-1}\sqrt{n_{core}^2 - n_{cladding}^2} = \sin^{-1} NA$$

Acceptance angle = $\sin^{-1}$ 0.244

ϕ_0 = $\mathbf{14.12^{o}}$ **…Ans.**

Types of Rays

- If the rays are launched within core of acceptance can be successfully propagated along the fiber. But the exact path of the ray is determined by the position and angle of ray at which it strikes the core.
  There exists three different types of rays.
  i) Skew rays ii) Meridional rays iii) Axial rays.

- **The skew rays** does not pass through the center, as show in Fig. 1.6.11 (a). The skew rays reflects off from the core cladding boundaries and again bounces around the outside of the core. It takes somewhat similar shape of spiral of helical path.

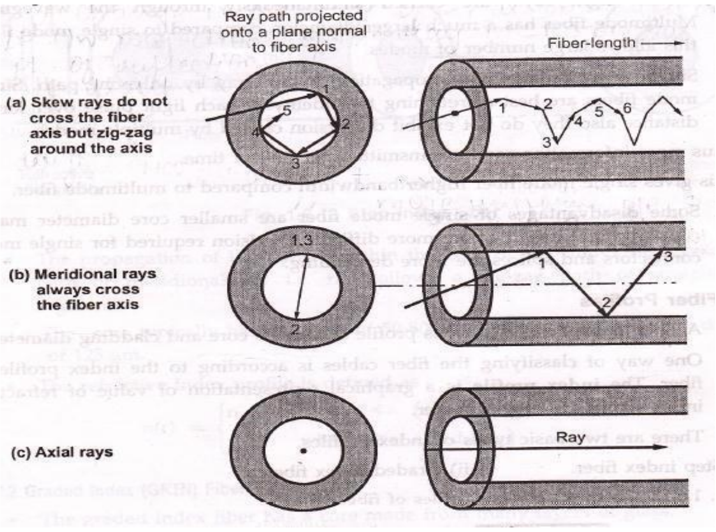


Fig:1.6.11 Different Ray Propagation

- The **meridional** ray enters the core and passes through its axis. When the core surface is parallel, it will always be reflected to pass through the enter. The meridional ray is shown in fig. 1.6.11 (b).
- The **axial ray** travels along the axis of the fiber and stays at the axis all the time. It is shown in fig. 1.6.11 (c).

Modes of Fiber

- Fiber cables cal also be classified as per their mode. Light rays propagate as an electromagnetic wave along the fiber. The two components, the electric field and the magnetic field form patterns across the fiber. These patterns are called **modes** of transmission. The **mode** of a fiber refers to the number of paths for the light rays within the cable. According to modes optic fibers can be classified into two types.

  i) Single mode fiber ii) Multimode fiber.

- Multimode fiber was the first fiber type to be manufactured and commercialized. The term multimode simply refers to the fact that numerous modes (light rays) are carried simultaneously through the waveguide. Multimode fiber has a much larger diameter, compared to single mode fiber, this allows large number of modes.
- Single mode fiber allows propagation to light ray by only one path. Single mode fibers are best at retaining the fidelity of each light pulse over longer distance also they do not exhibit dispersion caused by multiple modes.

Thus more information can be transmitted per unit of time.

This gives single mode fiber higher bandwidth compared to multimode fiber.

- Some disadvantages of single mode fiber are smaller core diameter makes coupling light into the core more difficult. Precision required for single mode connectors and splices are more demanding.

Fiber Profiles

- A fiber is characterized by its profile and by its core and cladding diameters.
- One way of classifying the fiber cables is according to the index profile at fiber. The **index profile** is a graphical representation of value of refractive index across the core diameter.
- There are two basic types of index profiles.

i) Step index fiber. ii) Graded index fiber.

Fig. 1.6.12 shows the index profiles of fibers.

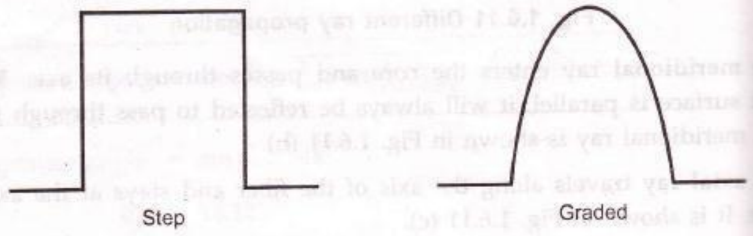


Fig. 1.6.12 Index profiles

Step Index (SI) Fiber

- The step index (SI) fiber is a cylindrical waveguide core with central or inner core has a uniform refractive index of n_1 and the core is surrounded by outer cladding with uniform refractive index of n_2. The cladding refractive index (n_2) is less than the core refractive index (n_1). But there is an abrupt change in the refractive index at the core cladding interface. Refractive index profile of step indexed optical fiber is shown in Fig. 1.6.13. The refractive index is plotted on horizontal axis and radial distance from the core is plotted on vertical axis.

- The propagation of light wave within the core of step index fiber takes the path of meridional ray i.e. ray follows a zig-zag path of straight line segments.

  The core typically has diameter of 50-80 µm and the cladding has a diameter of 125 µm.

- The refractive index profile is defined as –

$$n(r) = \begin{cases} n_1 & \text{when } r < a \text{ (core)} \\ n_2 & \text{when } r \geq a \text{ (cladding)} \end{cases}$$

Graded Index (GRIN) Fiber

- The graded index fiber has a core made from many layers of glass.
- In the **graded index (GRIN)** fiber the refractive index is not uniform within the core, it is highest at the center and decreases smoothly and continuously with distance towards the cladding. The refractive index profile across the core takes the parabolic nature. Fig. 1.6.14 shows refractive index profile of graded index fiber.

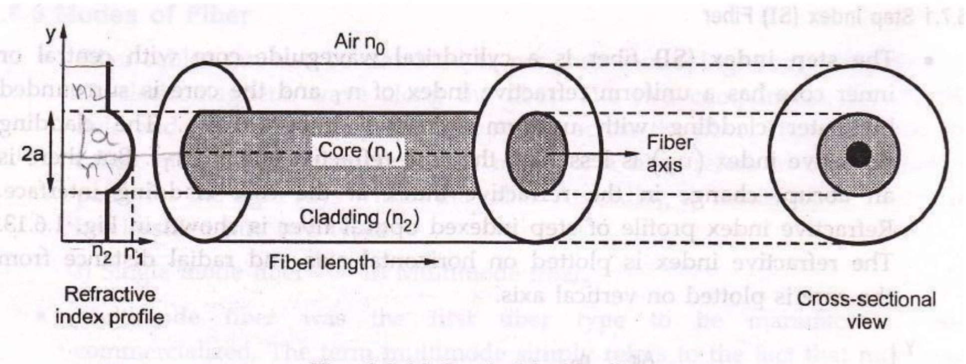


Fig. 1.6.14 Graded index fiber

- In graded index fiber the light waves are bent by refraction towards the core axis and they follow the curved path down the fiber length. This results because of change in refractive index as moved away from the center of the core.
- A graded index fiber has lower coupling efficiency and higher bandwidth than the step index fiber. It is available in 50/125 and 62.5/125 sizes. The 50/125 fiber has been optimized for long haul applications and has a smaller NA and higher bandwidth. 62.5/125 fiber is optimized for LAN applications which is costing 25% more than the 50/125 fiber cable.
- The refractive index variation in the core is giver by relationship

$$n(r) = \begin{cases} n_1\left(1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right) & \text{when } r < a \text{ (core)} \\ n_1(1 - 2\Delta)^{\frac{1}{2}} \approx n_2 & \text{when } r \geq a \text{ (cladding)} \end{cases}$$

where,

= Radial distance from fiber axis

a = Core radius

n_1= Refractive index of core

n_2 = Refractive index of cladding α

= Shape of index profile.

- Profile parameter α determines the characteristic refractive index profile of fiber core. The range of refractive index as variation of α is shown in Fig. 1.6.1

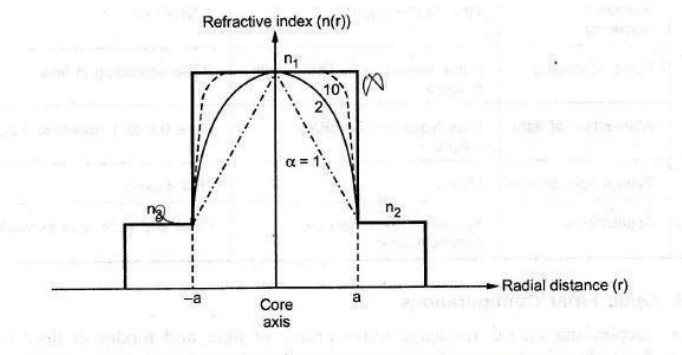


Fig. 1.6.15 Possible fiber refractive index profiles for different values of α

Comparison of Step Index and Graded Index Fiber

Sr. No.	Parameter	Step index fiber	Graded index fiber
1.	Data rate	Slow.	Higher
2.	Coupling efficiency	Coupling efficiency with fiber is higher.	Lower coupling efficiency.
3.	Ray path	By total internal reflection.	Light travelled oscillatory fashion.
4.	Index variation		
5.	Numerical aperture	NA remains same.	Changes continuously distance from fiber axis.
6.	Material used	Normally plastic or glass is preferred.	Only glass is preferred.
7.	Bandwidth efficiency	10 – 20 MHz/km	1 GHz/km

8.	Pulse spreading	Pulse spreading by fiber length is more.	Pulse spreading is less
9.	Attenuation of light	Less typically 0.34 dB/km at 1.3 µm.	More 0.6 to 1 dB/km at 1.3 µm.
10	Typical light source	LED.	LED, Lasers.
	Applications	Subscriber local network communication.	networks.

Optic Fiber Configurations

- Depending on the refractive index profile of fiber and modes of fiber there exist three types of optical fiber configurations. These optic-fiber configurations are -

i) Single mode step index fiber.
ii) Multimode step index fiber.
iii) Multimode graded index fiber.

Single mode Step index Fiber

- In single mode step index fiber has a central core that is sufficiently small so that there is essentially only one path for light ray through the cable. The light ray is propagated in the fiber through reflection. Typical core sizes are 2 to 15 µm. Single mode fiber is also known as fundamental or monomode fiber.

Fig. 1.6.16 shows single mode fiber.

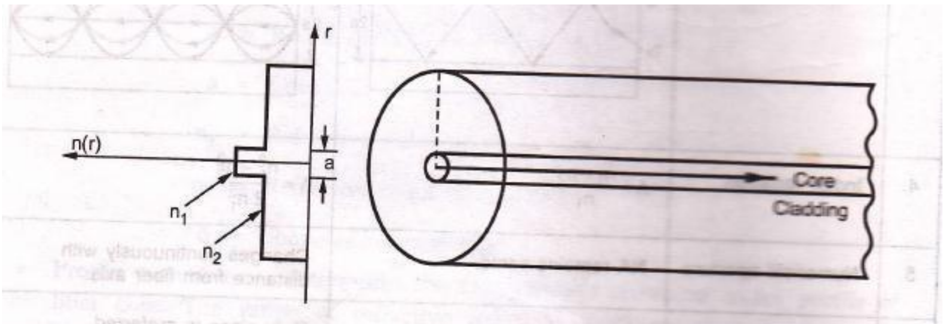


Fig. 1.6.16 The refractive index profile and ray transmission in single mode step index fiber

- Single mode fiber will permit only one mode to propagate and does not suffer from mode delay differences. These are primarily developed for the 1300 nm window but they can be also be used effectively with time division multiplex (TDM) and wavelength division multiplex (WDM) systems operating in 1550 nm wavelength region.
- The core fiber of a single mode fiber is very narrow compared to the wavelength of light being used. Therefore, only a single path exists through the cable core through which light can travel. Usually, 20 percent of the light in a single mode cable actually

  travels down the cladding and the effective diameter of the cable is a blend of single mode core and degree to which the cladding carries light. This is referred to as the 'mode field diameter', which is larger than physical diameter of the core depending on the refractive indices of the core and cladding.

- The disadvantage of this type of cable is that because of extremely small size interconnection of cables and interfacing with source is difficult. Another disadvantage of single mode fibers is that as the refractive index of glass decreases with optical wavelength, the light velocity will also be wavelength dependent. Thus the light from an optical transmitter will have definite spectral width.

Multimode step Index Fiber

- **Multimode step index fiber** is more widely used type. It is easy to manufacture. Its core diameter is 50 to 1000 µm i.e. large aperture and allows more light to enter the cable. The light rays are propagated down the core in zig-zag manner. There are many many paths that a light ray may follow during the propagation.
- The light ray is propagated using the principle of total internal reflection (TIR). Since the core index of refraction is higher than the cladding index of refraction, the light enters at less than critical angle is guided along the fiber.

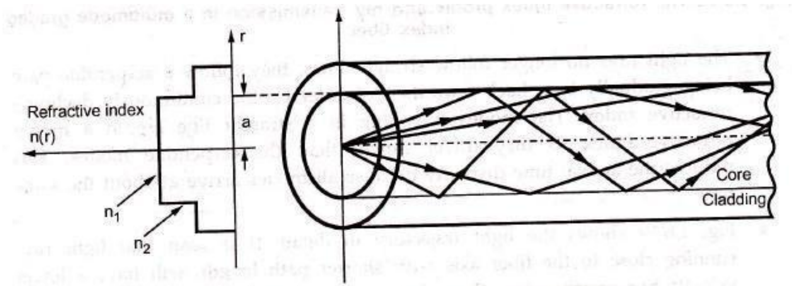


Fig. 1.6.17 TIR in multimode step index fiber

- Light rays passing through the fiber are continuously reflected off the glass cladding towards the centre of the core at different angles and lengths, limiting overall bandwidth.
- The disadvantage of multimode step index fibers is that the different optical lengths caused by various angles at which light is propagated relative to the core, causes the

transmission bandwidth to be fairly small. Because of these limitations, multimode step index fiber is typically only used in applications requiring distances of less than 1 km.

Multimode Graded Index Fiber

- The core size of **multimode graded index fiber** cable is varying from 50 to 100 µm range. The light ray is propagated through the refraction. The light ray enters the fiber at

  many different angles. As the light propagates across the core toward the center it is intersecting a less dense to more dense medium. Therefore the light rays are being constantly being refracted and ray is bending continuously. This cable is mostly used for long distance communication.

Fig 1.6.18 shows multimode graded index fiber.

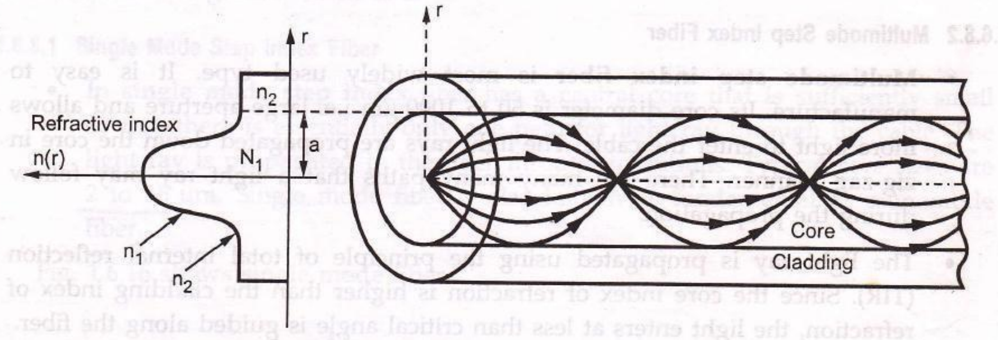


Fig. 1.6.18 The refractive index profile and ray transmission in a multimode graded index fiber

- The light rays no longer follow straight lines, they follow a serpentine path being gradually bent back towards the center by the continuously declining refractive index. The modes travelling in a straight line are in a higher refractive index so they travel slower than the serpentine modes. This reduces the arrival time disparity because all modes arrive at about the same time.
- Fig 1.6.19 shows the light trajectory in detail. It is seen that light rays running close to the fiber axis with shorter path length, will have a lower velocity because they pass through a region with a high refractive index.

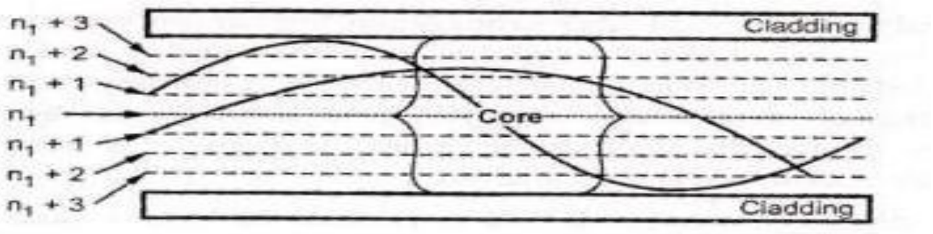


Fig. 1.6.19 Light trajectories in a graded index fiber

Rays on core edges offers reduced refractive index, hence travel more faster than axial rays and cause the light components to take same amount of time to travel the length of fiber, thus minimizing dispersion losses. Each path at a different angle is termed as

'transmission mode' and the NA of graded index fiber is defined as the maximum value of acceptance angle at the fiber axis.

- Typical attenuation coefficients of graded index fibers at 850 nm are 2.5 to 3 dB/km, while at 1300 nm they are 1.0 to 1.5 dB/km.
- The main advantages of graded index fiber are:

1. Reduced refractive index at the centre of core.
2. Comparatively cheap to produce.

Standard fibers

Sr. No.	**Fiber type**	**Cladding Diameter (μm)**	**Core diameter (μm)**		**Applications**
1.	Single mode (8/125)	125	8	0.1% to 0.2%	1. Long distance 2. High data rate
2.	Multimode (50/125)	125	50	1% to 2%	1. Short distance 2. Low data rate
3.	Multimode (62.5/125)	125	62.5	1% to 2%	LAN
4.	Multimode (100/140)	140	100	1% to 2%	LAN

Mode Theory for Cylindrical Waveguide

- To analyze the optical fiber propagation mechanism within a fiber, Maxwell equations are to solve subject to the cylindrical boundary conditions at core-cladding interface. The core-cladding boundary conditions lead to coupling of electric and magnetic field components resulting in hybrid modes. Hence the analysis of optical waveguide is more complex than metallic hollow waveguide analysis.
- Depending on the large E-field, the hybrid modes are HE or EH modes. The two lowest order does are HE_{11} and TE_{01}.

Overview of Modes

- The order states the number of field zeros across the guide. The electric fields are not completely confined within the core i.e. they do not go to zero at core-cladding interface and extends into the cladding. The low order mode confines the electric field near the axis of the fiber core and there is less penetration into the cladding. While the high order mode distribute the field towards the edge of the core fiber and penetrations into the cladding. Therefore cladding modes also appear resulting in power loss.
- In leaky modes the fields are confined partially in the fiber core attenuated as they propagate along the fiber length due to radiation and tunnel effect.
- Therefore in order to mode remain guided, the propagation factor β must satisfy the condition

$$n_2k < \beta < n_1k$$

n_1 = Refractive index of fiber core

where,

n_2 = Refractive index of cladding k =

Propagation constant = 2π / λ

- The cladding is used to prevent scattering loss that results from core material discontinuities. Cladding also improves the mechanical strength of fiber core and reduces
surface contamination. Plastic cladding is commonly used. Materials used for fabrication of optical fibers are silicon dioxide (SiO_2), boric oxide-silica.

Summary of Key Modal Concepts

- Normalized frequency variable, V is defined as

$$V = \frac{2\pi a(n_1^2 - n_2^2)^{1/2}}{\lambda}$$

where, a = Core radiu Free space wav

(1.7

.1)

$$\boxed{V = \frac{2\pi a}{\lambda} NA}$$ Since $(n_1^2 - n_2^2)^{1/2}$ = NA ... (1.7.2)

- The total number of modes in a multimode fiber is given by

$$M = \frac{1}{2}\left(\frac{2\pi a}{\lambda}\right)^2 (n_1^2 - n_2^2)$$

$$M = \frac{1}{2}\left[\frac{2\pi\, a}{\lambda} NA\right]^2 = \frac{[V]^2}{2}$$

$$M = \frac{1}{2}\left[\frac{\pi d}{\lambda}.NA\right]^2$$

Example 1.7.1 : Calculate the number of modes of an optical fiber having diameter of 50 µm, $n_1 = 1.48$, $n_2 = 1.46$ and $\lambda = 0.82$ µm.

Solution : d = 50 µm

$n_1 = 1.48$

$n_2 = 1.46$

$\lambda = 0.82$ µm

$$NA = (n_1^2 - n_2^2)^{1/2}$$

$$NA = (1.48^2 - 1.46^2)^{1/2}$$

$$NA = 0.243$$

Number of modes are given by,

$$M = \frac{1}{2}\left[\frac{\pi d}{\lambda}.NA\right]^2$$

$$M = \frac{1}{2}\left[\frac{\pi\,(50 \times 10^{-6})}{0.82 \times 10^{-6}} \times 0.243\right]^2$$

M = 1083 …Ans.

Example 1.7.2 : A fiber has normalized frequency V = 26.6 and the operating wavelength is 1300nm. If the radius of the fiber core is 25 µm. Compute the numerical aperture.

Solution : $V = 26.6$

$\lambda = 1300$ nm $= 1300 \times 10^{-9}$ m

$a = 25$ µm $= 25 \times 10^{-6}$ m

$$V = \frac{2\pi a}{\lambda} NA$$

$$NA = V.\frac{\lambda}{2\pi a}$$

$$NA = 26.6\,\frac{1300 \times 10^{-9}}{2\pi \times 25 \times 10^{-6}}$$

NA = **0.220** **… Ans.**

Example 1.7.3 : A multimode step index fiber with a core diameter of 80 µm and a relative index difference of 1.5 % is operating at a wavelength of 0.85 µm. If the core refractive index is 1.48, estimate the normalized frequency for the fiber and number of guided modes.

[July/Aug.-2008, 6 Marks]

Solution : Given : MM step index fiber, 2 a = 80 µm

∴ Core radians a = 40 µm

Relative index difference, = 1.5% = 0.015

Wavelength, λ = 0.85µm

Core refractive index, n1 = 1.48

Normalized frequency, V = ?

Number of modes, M = ?

Numerical aperture

$$\boxed{NA = n_1 (2\Delta)^{1/2}}$$

$$= 1.48\ (2 \text{ X } 0.015)^{1/2}$$

$$= 0.2563$$

Normalized frequency is given by,

$$\boxed{V = \frac{2\pi a}{\lambda} NA}$$

$$V = \frac{2\pi \text{ X } 40}{0.85} \text{ x } 0.2563$$

$$V = 75.78$$ **… Ans.**

Number of modes is given by,

$$\boxed{M = \frac{V^2}{2}}$$

$$M = \frac{(75.78)^2}{2} = \mathbf{2871.50}$$ **Ans**

Example 1.7.4 : A step index multimode fiber with a numerical aperture of a 0.20 supports approximately 1000 modes at an 850 nm wavelength.

i) What is the diameter of its core?
ii) How many modes does the fiber support at 1320 nm?
iii) How many modes does the fiber support at 1550 nm? **[Jan./Feb.-2007, 10 Marks]**

Solution : i) Number of modes is given by,

$$M = \frac{1}{2}\left[\frac{\pi\, a}{\lambda} . NA\right]^2$$

a = **60.49 µm … Ans.**

ii)

$$M = \frac{1}{2}\left[\frac{\pi \text{ X } 60.49 \text{ X } 10^{-6}}{1320 \text{ X } 10^{-9}} \text{ X } 0.20\right]^2$$

M = $(14.39)^2$ = **207.07**

iii)

$$M = \frac{1}{2}\left[\frac{\pi \text{ X } 6.49 \text{ X } 10^{-6}}{1320 \text{ X } 10^{-9}} \text{ X } 0.20\right]^2$$

M = **300.63**

Wave Propagation

Maxwell’s Equations

Maxwell’s equation for non-conducting medium:

∇ X E = - ∂B / X

∇ H = - ∂D /

∇ . D = 0

∇. B 0

where,

E and H are electric and magnetic field vectors.

- The relation between flux densities and filed

  vectors: $D = \varepsilon_0 E + P$

  $B = \mu_0 H + M$

where,

ε_0 is vacuum permittivity.

μ_0 is vacuum permeability.

P is induced electric polarization.

M is induced magnetic polarization (M = 0, for non-magnetic silica glass)

- P and E are related by:

$$P(r,t) = \varepsilon_0 \int_{-\infty}^{\infty} X(r,t-t')E\,(r,t')dt'$$

Where,

X is linear susceptibility.

- Wave equation:

$$\nabla \times \nabla \times E = \frac{-1}{c^2}\frac{\partial^2 E}{\partial E^2} - \mu_0 \frac{\partial^2 P}{\partial t^2}$$

Fourier transform of E (r, t)

$$\tilde{E}\,(r,\omega) = \int_{-\infty}^{\infty} E\,(r,t)e^{i\omega t}\,dt$$

$$\nabla \times \nabla \times \tilde{E} = -\,\varepsilon\,(r,\omega)\frac{\omega^2}{c^2}\tilde{E}$$

where,

$$\varepsilon = \left(n + \frac{i\alpha c}{2\omega}\right)^2$$

n is refractive index.

α is absorption coefficient.

$$n = \sqrt{(1 + R_e\chi)}$$

$$\alpha = \left(\frac{\omega}{nc}\right) I_m\,\chi$$

- Both n and α are frequency dependent. The frequency dependence of n is called as chromatic dispersion or material dispersion.
- For step index fiber,

$$\nabla \times \nabla \times \tilde{E} = \nabla (\nabla . \tilde{E}) - \nabla^2 . \tilde{E} = -\nabla^2 \tilde{E}$$

Fiber Modes

Optical mode : An optical mode is a specific solution of the wave equation that satisfies boundary conditions. There are three types of fiber modes.

a) Guided modes
b) Leaky modes
c) Radiation modes

- For fiber optic communication system guided mode is sued for signal transmission.

Considering a step index fiber with core radius ‘a’.

The cylindrical co-ordinates ρ, ϕ and can be used to represent boundary conditions.

$$\frac{\partial^2 E_z}{\partial \rho^2} + \frac{1}{\rho} \cdot \frac{\partial E_z}{\partial \rho} + \frac{1}{\rho^2} \cdot \frac{\partial^2 E_z}{\partial \phi^2} + \frac{\partial^2 E_z}{\partial z^2} + n^2 k_0^2 E_z = 0$$

- The refractive index ‘n’ has values

$$n = \begin{cases} n_1; & \rho \le a \\ n_2; & \rho > a \end{cases}$$

- The general solutions for boundary condition of optical field under guided mode is

infinite at $\rho = 0$ and decay to zero at $\rho = \infty$. Using Maxwell’s equation in the core region.

$$E_\rho = \frac{i}{p^2}\left(\beta \frac{\partial E_z}{\partial \rho} + \mu_0 \frac{\omega}{\rho} \cdot \frac{\partial H_z}{\partial \phi}\right)$$

- The **cut-off condition** is defined as –

$$V = k_0 a \sqrt{(n_1^2 - n_2^2)}$$

$$V = \left(\frac{2\pi}{\lambda}\right) a\, n_1 \sqrt{2\Delta}$$

It is also called as **normalized frequency**.

Graded Index Fiber Structure

- The Refractive index of graded index fiber decreases continuously towards its radius from the fiber axis and that for cladding is constant.

$$n(r) = \begin{cases} n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{\frac{1}{2}}, & when\ 0 \le r \le a \\ n_1(1-2\Delta)^{\frac{1}{2}} \approx n_1(1-\Delta) = n_2, & when\ r \ge a \end{cases}$$

- The refractive index variation in the core is usually designed by using power law relationship.Where, r = Radial distance from fiber axis

a = Core radius

n1 = Refractive index core

n2 Refractive index of cladding and α

= The shape of the index profile

- For graded index fiber, the index difference is given by,

- In graded index fiber the incident light will propagate when local numerical aperture at distance r from axis, NA is axial numerical aperture NA(0). The local numerical aperture is given as,

$$NA(r) = \begin{cases} [n^2(r) - n_2^2]^{\frac{1}{2}} \approx NA(0)\sqrt{1 - \left(\frac{r}{a}\right)^{\alpha}}, & for\ r \le a \\ 0, & for\ r > a \end{cases}$$

- The axial numerical aperture NA(0) is given as,

$$NA(0) = [n^2(0) - n_2^2]^{1/2}$$

$$NA(0) = [n_1^2 - n_2^2]^{1/2}$$

$$NA(0) = n_1\sqrt{2\Delta} \approx n_1(2\Delta)^{1/2}$$

Hence Na for graded index decreases to zero as it moves from fiber axis to core-cladding boundary.

- The variation of NA for different values of α is shown in Fig. 1.7.1.

- The number of modes for graded index fiber in given as,

$$\boxed{M = \frac{\alpha}{\alpha + 2} a^2 k^2 n_1^2 \Delta} \quad \ldots$$

Single Mode Fibers

- Propagation in single mode fiber is advantageous because signal dispersion due to delay differences amongst various modes in multimode is avoided. Multimode step index fibers cannot be used for single mode propagation due to difficulties in maintaining single mode operation. Therefore for the transmission of single mode the fiber is designed to allow propagation in one mode only, while all other modes are attenuated by leakage or absorption.
- For single mode operation, only fundamental LP_{01} mode many exist. The single mode propagation of LP_{01} mode in step index fibers is possible over the range.

$$0 \leq V < 2405$$

- The normalized frequency for the fiber can be adjusted within the range by reducing core radius and refractive index difference < 1%. In order to obtain single mode operation with maximum V number (2.4), the single mode fiber must have smaller core diameter than the equivalent multimode step index fiber. But smaller core diameter has problem of launching light into the fiber, jointing fibers and reduced relative index difference.

- Graded index fibers can also be sued for single mode operation with some special fiber design. The cut-off value of normalized frequency Vc in single mode operation for a graded index fiber is given by,

$$V_c = 2.405\left(1+\frac{2}{\alpha}\right)^{\frac{1}{2}}$$

Example 1.8.1 : A multimode step index optical fiber with relative refractive index difference 1.5% and core refractive index 1.48 is to be used for single mode operation. If the operating wavelength is 0.85μm calculate the maximum core diameter.

Solution : Given :

$n_1 = 1.48$

$\Delta = 1.5\ \% = 0.015$

$\lambda = 0.85\ \mu m = 0.85 \times 10^{-6}\ m$

Maximum V value for a fiber which gives single mode operations is 2.4. Normalized frequency (V number) and core diameter is related by expression,

$$V = \frac{2\pi}{\lambda} a\,(\mathrm{NA})$$

$$\boxed{V = \frac{2\pi}{\lambda} a\, n_1 (2\Delta)^{\frac{1}{2}}}$$

$$a = \frac{V\lambda}{2\pi\, n_1 (2\Delta)^{\frac{1}{2}}}$$

$$a = \frac{2.4 \times (0.85 \times 10^{-6})}{2\pi \times (1.48) \times (0.03)^{\frac{1}{2}}}$$

a = **1.3 μm** **… Ans.**

Maximum core diameter for single mode operation is 2.6 μm.

Example 1.8.2 : A GRIN fiber with parabolic refractive index profile core has a refractive index at the core axis of 1.5 and relative index difference at 1%. Calculate maximum possible core diameter that allows single mode operations at λ = 1.3 µm.

Solution : Given :

$$n_1 = 1.5$$

$$\Delta = 1\ \% = 0.01$$

$$\lambda = 1.3\ \mu m = 1.3 \text{ x } 10^{-6}\text{m}$$

for a GRIN

Maximum value of normalized frequency for single mode operation is given by,

$$V = 2.4\left(1+\frac{2}{\propto}\right)^{\frac{1}{2}}$$

Maximum core radius is given by expression,

$$a = \frac{V\lambda}{2\pi\, n_1 (2\Delta)^{\frac{1}{2}}}$$

$$a = \frac{24\sqrt{2} \text{ x } 1.3 \text{ x } 10^{-6}}{2\pi \text{ x } 1.5 \text{ x } (0.02)^{\frac{1}{2}}}$$

a = 3.3 µm **… Ans.**

∴ Maximum core diameter which allows single mode operation is 6.6 µm.

Cut-off Wavelength

- One important transmission parameter for single mode fiber us cut-off wavelength for the first higher order mode as it distinguishes the single mode and multim0de regions.
- The effective cut-off wavelength λ_C is defined as the largest wavelength at which higher order $(L_{P_{11}})$ mode power relative to the fundamental mode $(L_{P_{01}})$ power is reduced to 0.1 dB. The range of cut-off wavelength recommended to avoid modal noise and dispersion problems is : 1100 to 1280 nm (1.1 to 1.28µm) for single mode fiber at 1.3 µm.
- The cut-off wavelength λ_C can be computed from expression of

normalized frequency.

…. (1.8.1)

∴ …. (1.8.2)

$$\lambda = \frac{2\pi a n_1}{V}(2\Delta)^{\frac{1}{2}}$$

where,

V_C is cut-off normalized frequency.

- λ_C is the wavelength above which a particular fiber becomes single moded. For same fiber dividing λ_C by λ we get the relation as:

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_C}$$

$$\lambda = \frac{v\lambda}{v_C} \qquad \text{… (1.8.3)}$$

But for step index fiver V_C = 2.405 then

$$\lambda_c = \frac{v\lambda}{2.405}$$

Example 1.8.3 : Estimate cut-off wavelength for step index fiber in single mode operation. The core refractive index is 1.46 and core radius is 4.5 µm. The relative index difference is 0.25 %.

Solutions : Given :

n_1 = 1.46

a = 4.5 µm

Δ = 0.25 % = 0.0025

Cut-off wavelength is given by,

$$\lambda_c = \frac{2\pi a n_1 (2\Delta)^{\frac{1}{2}}}{V_c}$$

For cut-off wavelength, V_C = 2.405

$$\lambda_c = \frac{2\pi \times 4.5 \times 1.46\,(0.005)^{\frac{1}{2}}}{2.405}$$

$$\lambda_c = 1.214\ \mu\text{m}$$

Mode Field Diameter and Spot Size

- The mode filed diameter is fundamental parameter of a single mode fiber. This parameter is determined from mode field distributions of fundamental

  LP_{01} mode.

- In step index and graded single mode fibers, the field amplitude distribution is approximated by Gaussian distribution. The **mode Field diameter** (MFD) is distance between opposite 1/e – 0.37 times the near field strength)amplitude) and power is $1/e^2 = 0.135$ times.

- In single mode fiber for fundamental mode, on field amplitude distribution the mode filed diameter is shown in fig. 1.8.1.

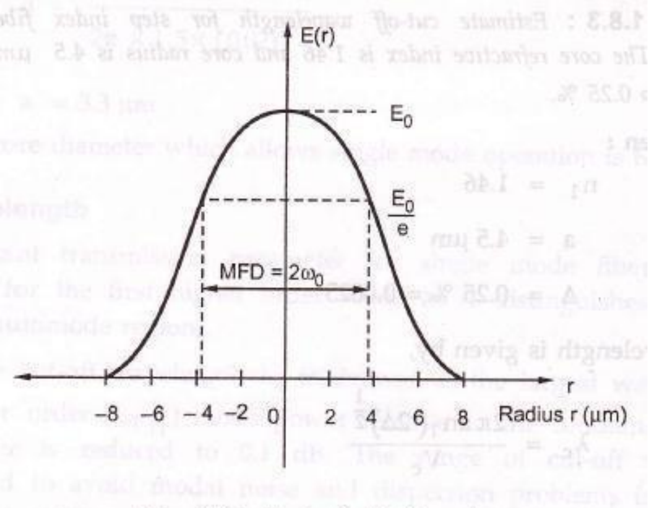


Fig. 1.8.1 Mode field diameter

- The spot size ω_0 is gives as –

$$\omega_0 = \frac{\text{MFD}}{2}$$

$$\text{MFD} = 2\,\omega_0$$

The parameter takes into account the wavelength dependent filed penetration into the cladding. Fig. 1.8.2 shows mode field diameters variation with λ.

UNIT - 2

SIGNAL DEGRADATION OPTICAL FIBERS.

Introduction

1. One of the important property of optical fiber is signal attenuation. It is also known as fiber loss or signal loss. The signal attenuation of fiber determines the maximum distance between transmitter and receiver. The attenuation also determines the number of repeaters required, maintaining repeater is a costly affair.
2. Another important property of optical fiber is distortion mechanism. As the signal pulse travels along the fiber length it becomes more broader. After sufficient length the broad pulses starts overlapping with adjacent pulses. This creates error in the receiver. Hence the distortion limits the information carrying capacity of fiber.

Attenuation

- Attenuation is a measure of decay of signal strength or loss of light power that occurs as light pulses propagate through the length of the fiber.
- In optical fibers the attenuation is mainly caused by two physical factors absorption and scattering losses. Absorption is because of fiber material and scattering due to structural imperfection within the fiber. Nearly 90 % of total attenuation is caused by Rayleigh scattering only. Microbending of optical fiber also contributes to the attenuation of signal.
- The rate at which light is absorbed is dependent on the wavelength of the light and the characteristics of particular glass. Glass is a silicon compound, by adding different additional chemicals to the basic silicon dioxide the optical properties of the glass can be changed.
- The Rayleigh scattering is wavelength dependent and reduces rapidly as the wavelength of the incident radiation increases.
- The attenuation of fiber is governed by the materials from which it is fabricated, the manufacturing process and the refractive index profile chosen. Attenuation loss is measured in dB/km.

Attenuation Units

- As attenuation leads to a loss of power along the fiber, the output power is significantly less than the couples power. Let the couples optical power is p(0) i.e. at origin (z = 0).

Then the power at distance z is given by,

$$P(z) = P(0)e^{-\propto_p z}$$

where, α_p is fiber attenuation constant (per km).

… (2.1.1

$$\propto_p = \frac{1}{z} \ln \left[\frac{P(0)}{P(z)}\right]$$

$$\boxed{\propto_{dB/km} = 10 . \frac{1}{z} \log \left[\frac{P(0)}{P(z)}\right]}$$

$$\propto_{dB/km} = 4.343 \ \propto_p \ \text{per km}$$

This parameter is known as fiber loss or fiber attenuation.

- Attenuation is also a function of wavelength. Optical fiber wavelength as a function of wavelength is shown in Fig. 2.1.1.

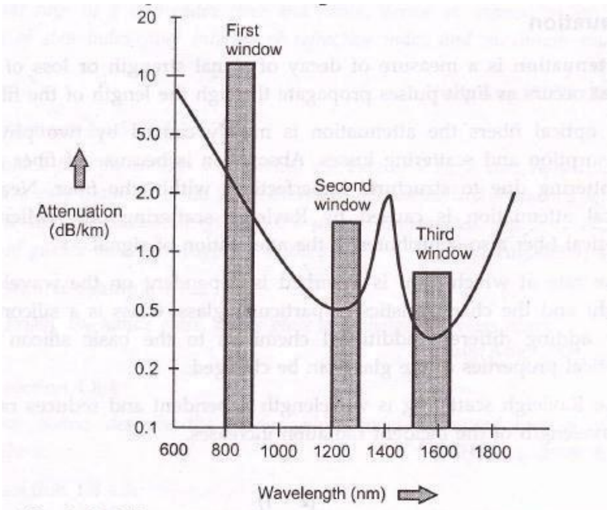


Fig. 2.1.1 Fiber attenuation as a function of wavelength

Example 2.1.1 : A low loss fiber has average loss of 3 dB/km at 900 nm. Compute the length over which –

a) Power decreases by 50 % b) Power decreases by 75 %.

Solution : $\alpha = 3$ dB/km

$$\Rightarrow \qquad \frac{p(0)}{p(z)} = 50\ \% = 0.5$$

a) Power decreases by 50 %.□ is given by,

$$\alpha = 10 \cdot \frac{1}{z} \log \left[\frac{P(0)}{P(z)}\right]$$

$$3 = 10 \cdot \frac{1}{z} \log [0.5]$$

∴

z = **1 km** **… Ans.**

b) $$\frac{P(0)}{P(z)} = 25\ \% = 0.25$$

Since power decrease by 75 %.

$$3 = 10 \times \frac{1}{z} \log[0.25]$$

∴ z = **2 km** **… Ans.**

Example 2.1.2 : For a 30 km long fiber attenuation 0.8 dB/km at 1300nm. If a 200 µwatt power is launched into the fiber, find the output power.

Solution : z = 30 km

□ = 0.8 dB/km

P(0) = 200 µW

$$\left[\frac{200\ \mu W}{P(z)}\right] = 10^{2.4}$$

Attenuation in optical fiber is given by,

$$\alpha = 10 \ x \ \frac{1}{} \ \log \left[\frac{P(0)}{}\right]$$

$$P(z) = \left[\frac{200 \ \mu W}{P(z)}\right] = 0.7962 \ \mu W$$

∴

$$0.8 = 10 \ x \ \frac{1}{30} \ \log \left[\frac{200 \ \mu W}{P(z)}\right]$$

$$2.4 = 10 \ x \ \log \left[\frac{200 \ \mu W}{P(z)}\right]$$

Example 2.1.3 : When mean optical power launched into an 8 km length of fiber is 12 µW, the mean optical power at the fiber output is 3 µW.

Determine –

☐ Overall signal attenuation in dB.

☐ The overall signal attenuation for a 10 km optical link using the same fiber with splices at 1 km intervals, each giving an attenuation of 1 dB.

Solution : **Given** : z = 8 km

P(0) = 120 µW

P(z) = 3 µW

1) Overall attenuation is given by,

$$\alpha = 10\ .\log\left[\frac{P(0)}{P(z)}\right]$$

$$\alpha = 10\ .\log\left[\frac{120}{3}\right]$$

$$\alpha = 16.02\ \text{dB}$$

2) Overall attenuation for 10 km,

Attenuation per km $\propto_{\text{dB}} = \frac{16.02}{z} = \frac{16.02}{8} = 2.00\ \text{dB/km}$

Attenuation in 10 km link = 2.00 x 10 = 20 dB

In 10 km link there will be 9 splices at 1 km interval. Each splice introducing attenuation of 1 dB.

Total attenuation = 20 dB + 9 dB = **29 dB**

Example 2.1.4 : A continuous 12 km long optical fiber link has a loss of 1.5 dB/km.

- What is the minimum optical power level that must be launched into the fiber to maintain as optical power level of 0.3 µW at the receiving end?
- What is the required input power if the fiber has a loss of 2.5 dB/km?

Solution : Given data : z = 12 km

= 1.5 dB/km

P(0) = 0.3 µW

- Attenuation in optical fiber is given by,

$$\alpha = 10 \text{ x } \frac{1}{z} \log\left(\frac{P(0)}{P(z)}\right)$$

$$1.5 = 10 \text{ x } \frac{1}{12} \log\left(\frac{0.3\ \mu W}{P(z)}\right)$$

$$\log\left(\frac{0.3\ \mu W}{P(z)}\right) = \frac{1.5}{0.833}$$

= 1.80

$$\left(\frac{0.3\ \mu W}{P(z)}\right) = 10^{1.8}$$

$$P(z) = \left(\frac{0.3\ \mu W}{10^{1.8}}\right) = \frac{0.3}{63.0}$$

$$P(z) = 4.76 \times 10^{-9} W$$

Optical power output = **4.76 x 10^{-9} W** **… Ans.**

ii) Input power = ? P(0)

When α = 2.5 dB/km

$$\boxed{\alpha = 10 \times \frac{1}{z} \log\left(\frac{P(0)}{P(z)}\right)}$$

$$2.5 = 10 \times \frac{1}{z} \log\left(\frac{P(0)}{4.76 \times 10^{-9}}\right)$$

$$\log\left(\frac{P(0)}{4.76 \times 10^{-9}}\right) = \frac{2.5}{0.833} = 3$$

$$\frac{P(0)}{4.76 \times 10^{-9}} = 10^{3} = 1000$$

∴ $P(0) = 4.76\ \mu W$

Input power= **4.76 µW** **… Ans.**

Example 2.1.5 : Optical power launched into fiber at transmitter end is 150 µW. The power at the end of 10 km length of the link working in first windows is – 38.2 dBm. Another system of same length working in second window is 47.5 µW. Same length system working in third window has 50 % launched power. Calculate fiber attenuation for each case and mention wavelength of operation. **[Jan./Feb.-2009, 4 Marks]**

Solution : Given data:

$P(0) = 150\ \mu W$

$z = 10\ km$

$$P(z) = -38.2\ dBm \Rightarrow \begin{cases} -38.2 = 10 \log \dfrac{P(z)}{1\ mW} \\ P(z) = 0.151\ \mu W \end{cases}$$

$z = 10\ km$

$$\boxed{\alpha = 10 \text{ x } \frac{1}{z} \log \left| \frac{P(0)}{P(z)} \right|}$$

Attenuation in 1st window:

$$\propto_1 = 10 \text{ x } \frac{1}{10} \log \left[\frac{150}{0.151} \right]$$

$$\boldsymbol{\propto_1 = 2.99\ dB/km}$$

Attenuation in 2nd window:

… Ans.

$$\propto_2 = 10 \ \text{x} \ \frac{1}{10} \log \left[\frac{150}{47.5}\right]$$

$$\propto_2 = \mathbf{0.49\ dB/km}$$

Attenuation in 3rd window:

… Ans.

$$\propto_3 = 10 \ \text{x} \ \frac{1}{10} \log \left[\frac{150}{75}\right]$$

$\alpha_3 = 0.30\ \mathrm{dB/km}$ **... Ans.**

Wavelength in 1^{st} window is 850 nm.

Wavelength in 2^{nd} window is 1300 nm.

Wavelength in 3^{rd} window is 1550 nm.

Example 2.1.6 : The input power to an optical fiber is 2 mW while the power measured at the output end is 2 µW. If the fiber attenuation is 0.5 dB/km, calculate the length of the fiber.

Solution : Given : P(0) = 2 mwatt = 2 x 10^{-3} watt

P(z) = 2 µwatt = 2 x 10^{-6} watt α

= 0.5 dB/km

$$\boxed{\alpha = 10 \text{ x } \frac{1}{z}\left[\frac{P(0)}{P(z)}\right]}$$

$$z = \mathbf{60\ km}$$ ... Ans.

$$0.5 = 10 \text{ x } \frac{1}{z}\log\left[\frac{2 \times 10^{-3}}{2 \times 10^{-6}}\right]$$

$$0.5 = \frac{1}{z} \text{x} 3$$

$$z = \frac{3}{0.05}$$

Absorption

- Absorption loss is related to the material composition and fabrication process of fiber. Absorption loss results in dissipation of some optical power as hear in the fiber cable. Although glass fibers are extremely pure, some impurities still remain as residue after purification. The amount of absorption by these impurities depends on their concentration and light wavelength.

- Absorption is caused by three different mechanisms.
  - Absorption by atomtic defects in glass composition.
  - Extrinsic absorption by impurity atoms in glass matts.
  - Intrinsic absorption by basic constituent atom of fiber.

Absorption by Atomic Defects

- Atomic defects are imperfections in the atomic structure of the fiber materials such as missing molecules, high density clusters of atom groups. These absorption losses are negligible compared with intrinsic and extrinsic losses.
- The absorption effect is most significant when fiber is exposed to ionizing radiation in nuclear reactor, medical therapies, space missions etc. The radiation dames the internal structure of fiber. The damages are proportional to the intensity of ionizing particles. This results in increasing attenuation due to atomic defects and absorbing optical energy. The total dose a material receives is expressed in rad (Si), this is the unit for measuring radiation absorbed in bulk silicon.

1 rad (Si) = 0.01 J.kg

The higher the radiation intensity more the attenuation as shown in Fig 2.2.1.

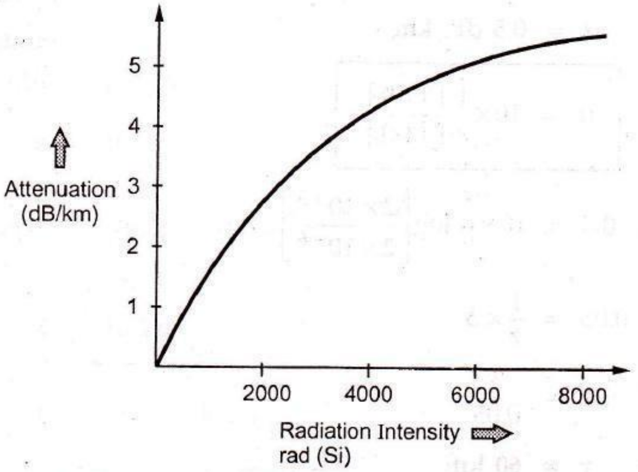


Fig. 2.2.1 Ionizing radiation intensity Vs fiber attenuation

Extrinsic Absorption

- Extrinsic absorption occurs due to electronic transitions between the energy level and because of charge transitions from one ion to another. A major source of attenuation is from transition of metal impurity ions such as iron, chromium, cobalt and copper. These losses can be upto 1 to 10 dB/km. The effect of metallic impurities can be reduced by glass refining techniques.

- Another major extrinsic loss is caused by absorption due to **OH (Hydroxil)** ions impurities dissolved in glass. Vibrations occur at wavelengths between 2.7 and 4.2 µm.

The absorption peaks occurs at 1400, 950 and 750 nm. These are first, second and third overtones respectively.

- Fig. 2.2.2 shows absorption spectrum for OH group in silica. Between these absorption peaks there are regions of low attenuation.

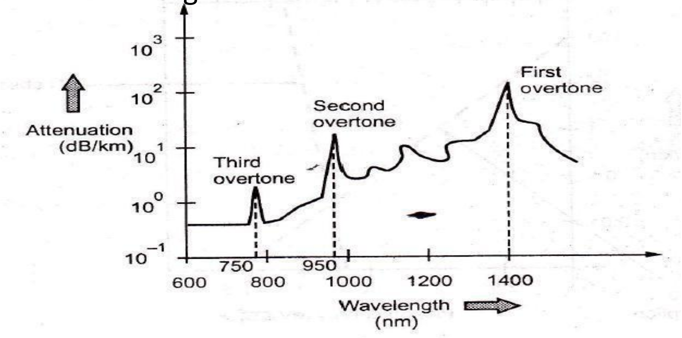


Fig. 2.2.2 Absorption spectra for OH group

Intrinsic Absorption

- Intrinsic absorption occurs when material is in absolutely pure state, no density variation and inhomogenities. Thus intrinsic absorption sets the fundamental lower limit on absorption for any particular material.
- Intrinsic absorption results from electronic absorption bands in UV region and from atomic vibration bands in the near infrared region.
- The electronic absorption bands are associated with the band gaps of amorphous glass materials. Absorption occurs when a photon interacts with an electron in the valene band and excites it to a higher energy level. UV absorption decays exponentially with increasing wavelength (λ).
- In the IR (infrared) region above 1.2 μm the optical waveguide loss is determined by presence of the OH ions and inherent IR absorption of the constituent materials. The inherent IR absorption is due to interaction between the vibrating band and the electromagnetic field of optical signal this results in transfer of energy from field to the band, thereby giving rise to absorption, this absorption is strong because of many bonds present in the fiber.

6. The ultraviolet loss at any wavelength is expressed as,

$$\propto_{uv} = \frac{154.2}{46.6\,x+60} \,x\, 10^{-2} \,x\, e^{\left(\frac{4.63}{\lambda}\right)} \qquad \text{… (2.2.1)}$$

where, x is mole fraction of GeO_2.

λ is operating wavelength.

α_{uv} is in dB/km.

9. The loss in infrared (IR) region (above 1.2 μm) is given by expression :

$$\propto_{IR} = 7.81 \text{ x } 10^{11} \text{ x } e^{\left(\frac{-48.48}{\lambda}\right)} \qquad \dots (2.2.2)$$

The expression is derived for GeO_2-SiO_2 glass fiber.

Rayleigh Scattering Losses

13. Scattering losses exists in optical fibers because of microscopic variations in the material density and composition. As glass is composed by randomly connected network of molecules and several oxides (e.g. SiO_2, GeO_2 and P_2O_5), these are the major cause of compositional structure fluctuation. These two effects results to variation in refractive index and Rayleigh type scattering of light.
14. **Rayleigh scattering** of light is due to small localized changes in the refractive index of the core and cladding material. There are two causes during the manufacturing of fiber.

3. The first is due to slight fluctuation in mixing of ingredients. The random changes because of this are impossible to eliminate completely.
4. The other cause is slight change in density as the silica cools and solidifies. When light ray strikes such zones it gets scattered in all directions. The amount of scatter depends on the size of the discontinuity compared with the wavelength of the light so the shortest wavelength (highest frequency) suffers most scattering. Fig. 2.3.1 shows graphically the relationship between wavelength and Rayleigh scattering loss.

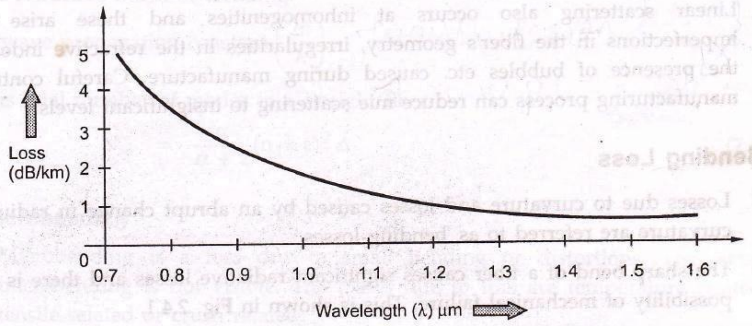


Fig. 2.3.1 Scattering loss

7. Scattering loss for single component glass is given by,

… (2.3.1)

$$\propto_{scat} = \frac{8\pi^3}{3\lambda^4}(n^2-1)^2 k_B T_f \beta_T \text{ nepers}$$

where, n = Refractive index

k_B = Boltzmann’s constant

β_T = Isothermal compressibility of material

T_f = Temperature at which density fluctuations are frozen into the glass as it solidifies (fictive temperature)

Another form of equation is

$$\propto_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 k_B T_f \beta_T \text{ neper} \propto_{scat} = \frac{8\pi^3}{3\lambda^4}(\delta_n^2)^2 \delta v \quad \text{… (2.3.2)}$$

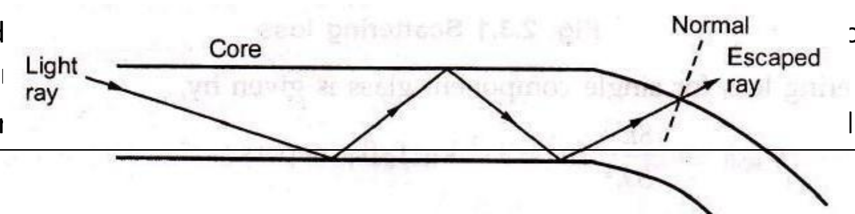
where, P = Photoelastic coefficient

where, δ_n^2 = Mean square refractive index fluctuation

δv = Volume of fiber

- Multimode fibers have higher dopant concentrations and greater compositional fluctuations. The overall losses in this fibers are more as compared to single mode fibers. **Mie Scattering :**
- Linear scattering also occurs at inhomogenities and these arise from imperfections in the fiber’s geometry, irregularities in the refractive index and the presence of bubbles etc. caused during manufacture. Careful control of manufacturing process can reduce mie scattering to insignificant levels.

Bending Loss



- Losses d of curvature are refe
- The sha lso

possibility of mechanical failure. This is shown in Fig. 2.4.1.

2 As the core bends the normal will follow it and the ray will now find itself on the wrong side of critical angle and will escape. The sharp bends are therefore avoided.

3 The radiation loss from a bent fiber depends on –

    Field strength of certain critical distance x_C from fiber axis where power is lost through radiation.

    The radius of curvature R.

4 The higher order modes are less tightly bound to the fiber core, the higher order modes radiate out of fiber firstly.

5 For multimode fiber, the effective number of modes that can be guided by curved fiber is where, α is graded index profile.

 is core – cladding index difference.

n_2 is refractive index of cladding.k is

wave propagation constant $\left(\frac{2\pi}{\lambda}\right)$.

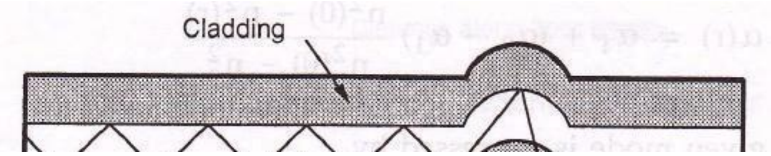
N_∞ is total number of modes in a straight fiber.

$$N_\infty = \frac{\alpha}{\alpha+2}(n_1\,k\,a)^2\Delta \qquad \ldots (2.4.2)$$

Microbending

- Microbending is a loss due to small bending or distortions. This small microbending is not visible. The losses due to this are temperature related, tensile related or crush related.
- The effects of microbending on multimode fiber can result in increasing attenuation (depending on wavelength) to a series of periodic peaks and troughs on the spectral attenuation curve. These effects can be minimized during installation and testing.

Fig. 2.4.2 illustrates microbening.



Macrobending

- The change in spectral attenuation caused by macrobending is different to microbending. Usually there are no peaks and troughs because in a macrobending no light is coupled back into the core from the cladding as can happen in the case of microbends.

- The macrobending losses are cause by large scale bending of fiber. The losses are eliminated when the bends are straightened. The losses can be minimized by not exceeding the long term bend radii. Fig. 2.4.3 illustrates macrobending.

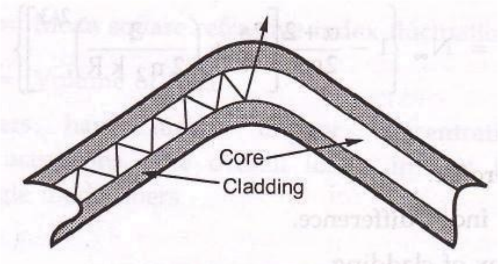


Fig. 2.4.3 Macrobending

Core and Cladding Loss

- Since the core and cladding have different indices of refraction hence they have different attenuation coefficients α1 and α2 respectively.
- For step index fiber, the loss for a mode order (v, m) is given by,

$$\alpha_{v\,m} = \alpha_1 \frac{P_{core}}{p} + \alpha_2 \frac{P_{cladding}}{p} \qquad \text{... (2.5.1)}$$

For low-order modes, the expression reduced to

$$\alpha_{v\,m} = \alpha_1 + (\alpha_2 + \alpha_1) \frac{P_{cladding}}{p} \qquad \text{... (2.5.2)}$$

where, $\frac{P_{core}}{P}$ and $\frac{P_{cladding}}{P}$ are fractional powers.

- For graded index fiber, loss at radial distance is expressed as,

$$\propto (r) = \propto_1 + (\propto_2 - \propto_1)\frac{n^2(0) - n^2(r)}{n^2(0) - n_2^2}$$

… (2.5.3)

The loss for a given mode is expressed by,

$$\propto_{\text{Graded Index}} = \frac{\int_0^\infty \propto(r)\, P(r)\, r\, dr}{\int_0^\infty P(r)\, r\, dr} \qquad \text{… (2.5.4)}$$

where, P(r) is power density of that model at radial distance r.

Signal Distortion in Optical Waveguide

- The pulse get distorted as it travels along the fiber lengths. Pulse spreading in fiber is referred as dispersion. Dispersion is caused by difference in the propagation times of light rays that takes different paths during the propagation. The light pulses travelling down the fiber encounter dispersion effect because of this the pulse spreads out in time domain. Dispersion limits the information bandwidth. The distortion effects can be analyzed by studying the group velocities in guided modes.

Information Capacity Determination

- Dispersion and attenuation of pulse travelling along the fiber is shown in Fig. 2.6.1.

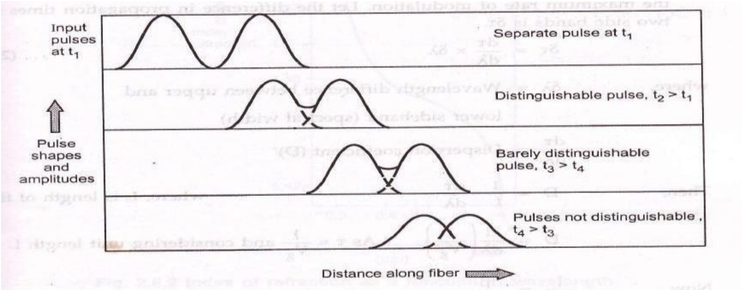


Fig. 2.6.1 Dispersion and attenuation in fiber

- Fig. 2.6.1 shows, after travelling some distance, pulse starts broadening and overlap with the neighbouring pulses. At certain distance the pulses are not even distinguishable and error will occur at receiver. Therefore the information capacity is specified by bandwidth- distance product (MHz . km). For step index bandwidth distance product is 20 MHz . km and for graded index it is 2.5 MHz . km.

Group Delay

- Consider a fiber cable carrying optical signal equally with various modes and each mode contains all the spectral components in the wavelength band. All the spectral components travel independently and they observe different **time delay** and **group delay** in the direction of propagation. The velocity at which the energy in a pulse travels along the fiber is known as **group velocity**. Group velocity is given by,

$$V_g = \frac{\partial w}{\partial \beta} \qquad \text{... (2.6.1)}$$

- Thus different frequency components in a signal will travel at different group velocities and so will arrive at their destination at different times, for digital modulation of carrier, this results in dispersion of pulse, which affects the maximum rate of modulation. Let the difference in propagation times for two side bands is δτ.

$$\delta\tau = \frac{d\tau}{d\lambda}\, x\, \delta\lambda \qquad \text{... (2.6.2)}$$

where, $\delta\tau$ = Wavelength difference between upper and lower sideband (spectral width) $\frac{d\tau}{d\lambda}$ = Dispersion coefficient (D)

Then, $D = \frac{1}{L} \cdot \frac{d\tau}{d\lambda}$ where, L is length of fiber.

$$D = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right)$$

As $\tau = \frac{1}{V_g}$ and considering unit length L = 1.

Now $\frac{1}{V_g} = \frac{d\beta}{d\omega}$

$$\frac{1}{V_g} = \frac{d\lambda}{d\omega} x \frac{d\beta}{d\lambda}$$

$$\frac{1}{V_g} = \frac{-\lambda^2}{2\pi c} x \frac{d\beta}{d\lambda}$$

∴

$$D = \frac{d}{d\lambda}\left(\frac{-\lambda^2}{2\pi c} \cdot \frac{d\beta}{d\lambda}\right) \qquad \text{... (2.6.3)}$$

- Dispersion is measured in picoseconds per nanometer per kilometer.

Material Dispersion

- Material dispersion is also called as chromatic dispersion. Material dispersion exists due to change in index of refraction for different wavelengths. A light ray contains components of various wavelengths centered at wavelength $\lambda10$. The time delay is different for different wavelength components. This results in time dispersion of pulse at the receiving end of fiber. Fig. 2.6.2 shows index of refraction as a function of optical wavelength.

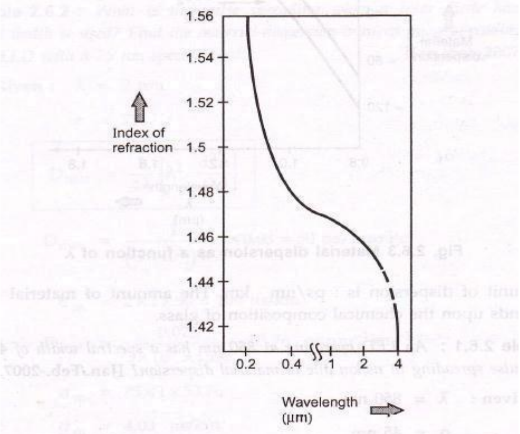


Fig. 2.6.2 Index of refraction as a function of wavelength

2. The material dispersion for unit length (L = 1) is given by

$$\boxed{D_{mat} = \frac{-\lambda}{c} x \frac{d^2n}{d\lambda^2}} \quad \text{… (2.6.4)}$$

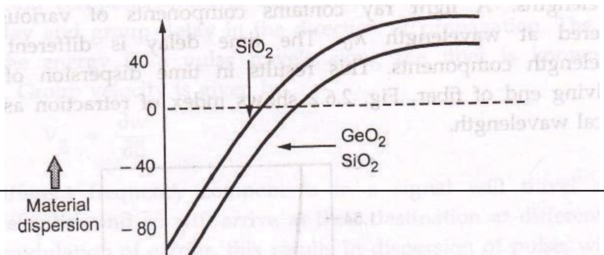
where, c = Light velocity

λ = Center wavelength

$\frac{d^2n}{d\lambda^2}$ = Second derivative of index of refraction w.r.t wavelength

Negative sign shows that the upper sideband signal (lowest wavelength) arrives before the lower sideband (highest wavelength).

- A plot of material dispersion and wavelength is shown in



- The unit of dispersion is : ps/nm . km. The amount of material dispersion depends upon the chemical composition of glass.

Example 2.6.1 : An LED operating at 850 nm has a spectral width of 45 nm. What is the pulse spreading in ns/km due to material dispersion? **[Jan./Feb.-2007, 3 Marks]**

Solution : Given : $\lambda = 850$ nm

$\sigma = 45$ nm

pulse broadening due to material dispersion is given by,

$\sigma_m = \sigma LM$

Considering length $L = 1$ metre

$$\boxed{\text{Material dispersion constant } D_{mat} = \frac{-\lambda}{c} \cdot \frac{d^2n}{d\lambda^2}}$$

For LED source operating at 850 nm, $\left|\lambda^2 \frac{d^2n}{d\lambda^2}\right| = 0.025$

∴ $$M = \frac{1}{c\lambda}\left|\lambda^2 \frac{d^2n}{d\lambda^2}\right| = \frac{1}{(3 \times 10^5)\,(850)} \times 0.025$$

M = 9.8 ps/nm/km

σ_m = **441 ns/km** **… Ans.**

Example 2.6.2 : What is the pulse spreading when a laser diode having a 2 nm spectral width is used? Find the the material-dispersion-induced pulse spreading at 1550 nm for an LED with a 75 nm spectral width **[Jan./Feb.-2007, 7 Marks]**

Solutions : Given : $\lambda = 2$ nm

$\sigma = 75$

$$\boxed{D_{mat} = \frac{1}{c\lambda}\left|\lambda^2 . \frac{d^2n}{d\lambda^2}\right|}$$

$$D_{mat} = \frac{1}{(3 \times 10^5) \times 2} \times 0.03 = 50 \text{ ps/nm/km}$$

$\sigma_m = 2 \times 1 \times 50 =$ **100 ns/km** **... Ans.**

For LED $$D_{mat} = \frac{0.025}{(3 \times 10^5) \times 1550} = 53.76 \text{ ps nm}^{-1}\text{km}^{-1}$$

$\sigma_m = 75 \times 1 \times 53.76$

$\sigma_m =$ **4.03 ns/km** **... Ans.**

Waveguide Dispersion

- Waveguide dispersion is caused by the difference in the index of refraction between the core and cladding, resulting in a 'drag' effect between the core and cladding portions of the power.
- Waveguide dispersion is significant only in fibers carrying fewer than 5-10 modes. Since multimode optical fibers carry hundreds of modes, they will not have observable waveguide dispersion.
- The group delay (τ_{wg}) arising due to waveguide dispersion.

$$(\tau_{wg}) = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d(kb)}{dk}\right] \quad \text{... (2.6.5)}$$

Where, b = Normalized propagation constant k

= 2π / λ (group velocity)

$$V = k\,a\,n_2\sqrt{2\Delta} \text{ (For small } \Delta)$$

Normalized frequency V,

$$V = ka(n_1^2 - n_2^2)^{\frac{1}{2}}$$

$$\therefore \qquad \tau_{wg} = \frac{L}{c}\left[n_2 + n_2 \Delta \frac{d(Vb)}{dV}\right] \qquad \text{... (2.6.6)}$$

The second term $\frac{d(V_b)}{dV}$ is waveguide dispersion and is mode dependent term..

- As frequency is a function of wavelength, the group velocity of the energy varies with frequency. The produces additional losses (waveguide dispersion). The propagation constant (b) varies with wavelength, the causes of which are independent of material dispersion.

Chromatic Dispersion

- The combination of material dispersion and waveguide dispersion is called chromatic dispersion. These losses primarily concern the spectral width of transmitter and choice of correct wavelength.
- A graph of effective refractive index against wavelength illustrates the effects of material, chromatic and waveguide dispersion.

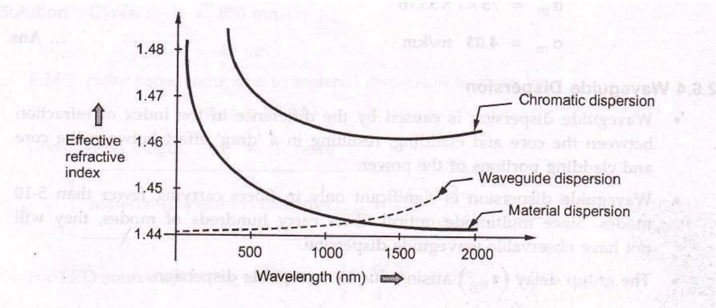


Fig. 2.6.4 Graph of effective refractive index against wavelength showing effects of chromatic, waveguide and material dispersion

- Material dispersion and waveguide dispersion effects vary in vary in opposite senses as the wavelength increased, but at an optimum wavelength around 1300 nm, two effects almost cancel each other and chromatic dispersion is at minimum. Attenuation is therefore also at minimum and makes 1300 nm a highly attractive operating wavelength.

Modal Dispersion

- As only a certain number of modes can propagate down the fiber, each of these modes carries the modulation signal and each one is incident on the boundary at a different angle, they will each have their own individual propagation times. The net effect is spreading of pulse, this form o dispersion is called modal dispersion.
- Modal dispersion takes place in multimode fibers. It is moderately present in graded index fibers and almost eliminated in single mode step index fibers.
- Modal dispersion is given by,

$$\boxed{\Delta t_{modal} = \frac{n_1 Z}{c}\left(\frac{\Delta}{1-\Delta}\right)}$$

where Δt_{modal} = Dispersion

n1 = Core refractive index Z

= Total fiber length

c = Velocity of light in air

□ = Fractional refractive index $\left(\frac{n_1 - n_2}{n_1}\right)$

Putting $\Delta = \frac{(NA^2)Z}{2n_1 c}$ in above equation

$$\boxed{\Delta t_{modal} = \frac{(NA^2)Z}{2n_1\ c}}$$

- The modal dispersion Δt_{modal} describes the optical pulse spreading due to modal effects optical pulse width can be converted to electrical rise time through the relationship.

$$t_{r\ mod} = 0.44\ (\Delta t_{modal})\pi r^2$$

Signal distortion in Single Mode Fibers

- The pulse spreading σ_{wg} over range of wavelengths can be obtained from derivative of group delay with respect t

$$\sigma_{wg} = \left|\frac{d\tau_{wg}}{d\lambda}\right| \sigma_{\lambda}$$

where,

$$\boxed{D_{wg}(\lambda) = \frac{-n_2\Delta}{c\lambda}\left[V\frac{d^2(Vb)}{dV^2}\right]}$$

... (2.6.8)

- This is the equation for waveguide dispersion for unit length.

Example 2.6.3 : For a single mode fiber n2 = 1.48 and = 0.2 % operating at A = 1320 nm, compute the waveguide dispersion if $V.\frac{d^2(Vb)}{dv^2} = 0.26.$

Solution : n2 = 1.48

0.2

□ = 1320 nm

Waveguide dispersion is given by,

$$D_{wg}(\lambda) = \frac{-n_2\Delta}{c\lambda}\left[V\frac{d^2(Vb)}{dV^2}\right]$$

$$= \frac{-1.48 \text{ x } 0.2}{3 \text{ x } 10^5 \text{ x } 1320}[0.20]$$

i) -1.943 picosec/nm .

km. Higher Order Dispersion

- Higher order dispersive effective effects are governed by dispersion slope S.

$$S = \frac{dD}{d\lambda}$$

where, D is total dispersion

Also, $S = \left(\frac{2\pi c}{\lambda^2}\right)^2 \beta_3 + \left(\frac{4\pi c}{\lambda^3}\right)\beta_2$

where,

β2 and β3 are second and third order dispersion parameters.

- Dispersion slope S plays an important role in designing WDM system

Dispersion Induced Limitations

- The extent of pulse broadening depends on the width and the shape of input pulses. The pulse broadening is studied with the help of wave equation.

Basic Propagation Equation

- The basic propagation equation which governs pulse evolution in a single mode fiber is given by,

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2} . \frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} = 0$$

where,

β_1, β_2 and β_3 are different dispersion parameters.

Chirped Gaussian Pulses

- A pulse is said to b e chirped if its carrier frequency changes with time.
- For a Gaussian spectrum having spectral width σ_ω, the pulse broadening factor is given by,

$$\frac{\sigma^2}{\sigma_0^2} = \left(1 + \frac{C\beta_2 L}{2\sigma_2^2}\right)^2 + (1 + V_\omega^2)\left(\frac{\beta_2 L}{2\sigma_0^2}\right)^2 + (1 + C + V_\omega^2)^2 \left(\frac{\beta_3 L}{4\sqrt{2\sigma_0^3}}\right)\pi r^2$$

where, $V_\omega = 2\sigma_\omega \sigma_0$

Limitations of Bit Rate

- The limiting bit rate is given by,

$$4B\sigma \leq 1$$

- The condition relating bit rate-distance product (BL) and dispersion (D) is given

$$BL\,|S|\,\sigma_{\lambda}^{2} \leq \frac{1}{\sqrt{8}}$$

where, S is dispersion slope.

- Limiting bit rate a single mode fibers as a function of fiber length for σλ = 0, a and 5nm is shown in fig. 2.6.5.

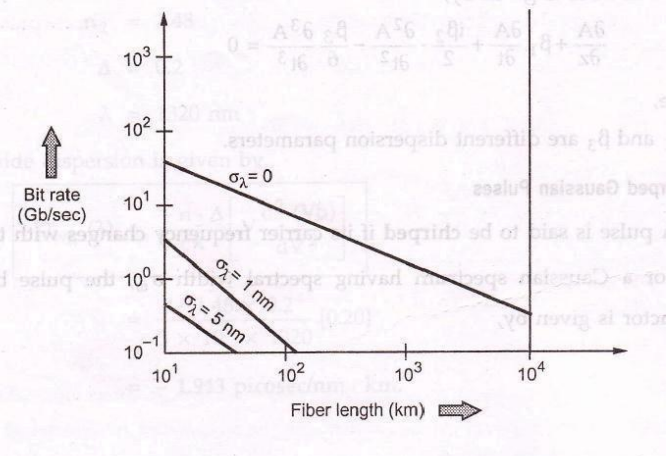


Fig. 2.6.5 Dependence of bit rate on fiber length

Polarization Mode Dispersion (PMD)

- Different frequency component of a pulse acquires different polarization state (such as linear polarization and circular polarization). This results in pulse broadening is kno**w as polarization mode dispersion (PMD).**
- PMD is the limiting factor for optical communication system at high data rates. The effects of PMD must be compensated.

Pulse Broadening in GI Fibers

- The core refractive index varies radially in case of graded index fibers, hence it supports multimode propagation with a low intermodal delay distortion and high data rate over long distance is possible. The higher order modes travelling in outer regions of the core, will travel faster than the lower order modes travelling in high refractive index region. If the index profile is carefully controlled, then the transit times of the individual modes will be identical, so eliminating modal dispersion.
- The r.m.s pulse broadening is given as:

$$\sigma = \left(\sigma^2_{\text{intermodal}} + \sigma^2_{\text{intermodal}}\right)^{1/2} \qquad \text{… (2.7.1)}$$

where,

$\sigma_{\text{intermodal}}$ – R.M.S pulse width due to intermodal delay distortion.

$\sigma_{\text{intermodal}}$ – R.M.S pulse width resulting from pulse broadening within each mode.

- The intermodal delay and pulse broadening are related by expression given by Personick.

$$\sigma_{\text{intermodal}} = \left(\langle\tau_g^2\rangle - \langle\tau_g\rangle^2\right)^{1/2} \qquad \text{… (2.7.2)}$$

Where τ_g is group delay.

From this the expression for intermodal pulse broadening is given as:

$$\propto_{\text{intermodal}} = \frac{LN_1\Delta}{2c} \cdot \frac{\propto}{\propto+1}\left(\frac{\propto+2}{3\propto+2}\right)^{1/2} \text{x}$$

$$\left[c_1^2 + \frac{4c_1c_2(\propto+1)}{2\propto+1} + \frac{16\Delta^2c_2^2(\propto+1)^2}{(5\propto+2)(3\propto+2)}\right]^{1/2} \qquad \text{… (2.7.3)}$$

$$c_1 = \frac{\propto-2-E}{\propto+2} \text{ and } c_2 = \frac{3\propto-2-2c}{2(\propto+2)}$$

- The intramodal pulse broadening is given as :

$$\sigma^2_{intramodal} = \left(\frac{\sigma\lambda}{\lambda}\right)^2 \left\langle\left(\lambda\frac{d\tau g}{d\lambda}\right)^2\right\rangle \qquad \text{… (2.7.4)}$$

Where σλ is spectral width of optical source.

Solving the expression gives :

$$\sigma^2_{intramodal} = \frac{L}{c} \cdot \frac{\sigma\lambda}{\lambda}\Bigg[\left(-\lambda^2\frac{d^2n_1}{d\lambda^2}\right)^2 - N_1c_1\Delta$$

$$\left(2\lambda^2 \frac{d^2 n_1}{d\lambda^2} \cdot \frac{\propto}{\propto+1} - N_1 c_1 \Delta \frac{4\propto^2}{(\propto+2)(3\propto+2)}\right)\Bigg]^{1/2}$$

Mode Coupling

- After certain initial length, the pulse distortion increases less rapidly because of mode coupling. The energy from one mode is coupled to other mods because of:
  - Structural imperfections.
  - Fiber diameter variations.
  - Refractive index variations.
  - Microbends in cable.
- Due to the mode coupling, average propagation delay become less and intermodal distortion reduces.
- Suppose certain initial coupling length = L_C, mode coupling length, over L_C = Z. Additional loss associated with mode coupling = h (dB/ km).

Therefore the excess attenuation resulting from mode coupling = hZ. The

improvement in pulse spreading by mode coupling is given as :

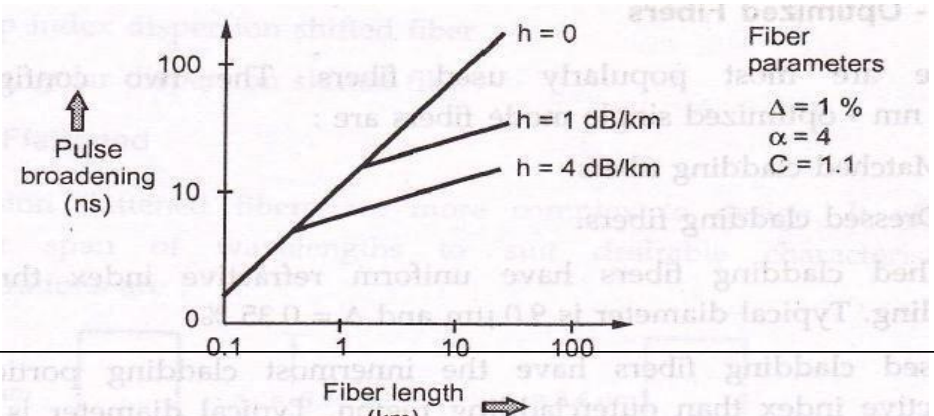
$$hZ\left(\frac{\sigma_c}{\sigma_0}\right) = C$$

where, C is constant independent of all dimensional quantities and refractive indices. σ_C is

pulse broadening under mode coupling.

σ_0 is pulse broadening in absence of mode coupling.

- For long fiber length’s the effect of mode coupling on pulse distortion is significant. For a graded index fiber, the effect of distance on pulse broading for various coupling losses are shown



Significant mode coupling occurs of connectors, splices and with other passive components of an optical link.

Design Optimization

- Features of single mode fibers are
  - : Longer life.
  - Low attenuation.
  - Signal transfer quality is good.
  - Modal noise is absent.
  - Largest BW-distance product.
- Basic design – optimization includes the following :
  - Cut-off wavelength.
  - Dispersion.
  - Mode field diameter.
  - Bending loss.
  - Refractive index profile.

Refractive Index Profile

- Dispersion of single mode silica fiber is lowest at 1300 nm while its attenuation is minimum at 1550 nm. For archiving maximum transmission distance the dispersion null should be at the wavelength of minimum attenuation. The waveguide dispersion is easier to control than the material dispersion. Therefore a variety of core-cladding refractive.

idex configuration fivers. Such as 1300 nm – optimized fibers, dispersion shifted fibers, dispersion – flattened fibers and large effective core area fibers.

☐ 1300 nm – Optimized Fibers

These are most popularly used fibers. The two configurations of 1300 nm – optimized single mode fibers are :

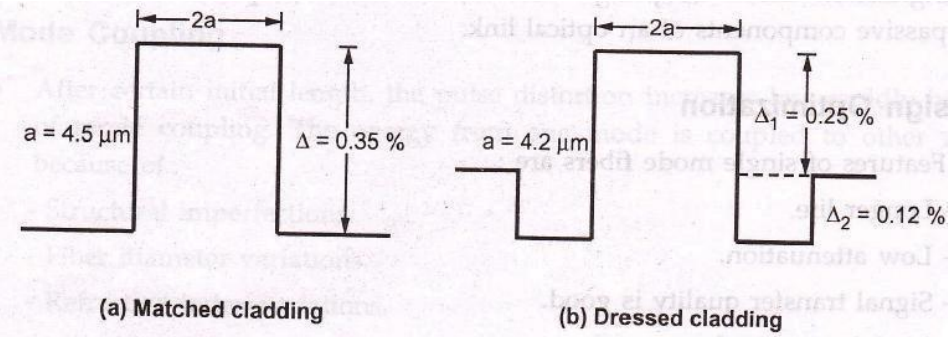
Matched cladding fibers.

Dressed cladding fibers.

Matched cladding fibers have uniform refractive index throughout its cladding. Typical diameter is 9.0 μm and $\Delta = 0.35$ %.

Dressed cladding fibers have the innermost cladding portion has low refractive index than outrcladding region. Typical diameter is 8.4 μm and $\Delta_1 = 0.25$ %, $\Delta_2 = 0.12$ %.

Fig 2.9.1 shows both types of fibers.

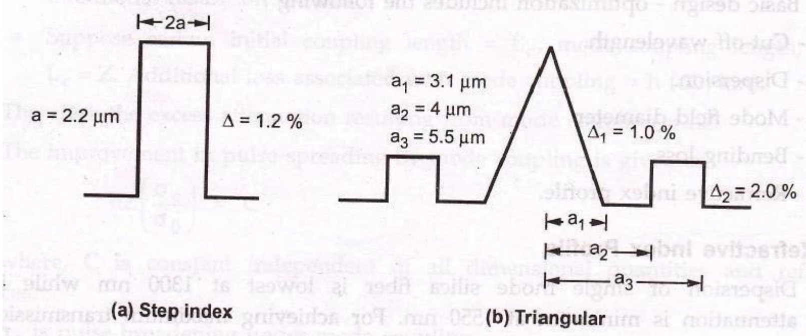


(a) Matched cladding

(b) Dressed cladding

Fig. 2.9.1 1300 nm - optimized refractive index profile

2. Dispersion Shifted Fibers



(a) Step index

(b) Triangular

Fig. 2.9.2 Dispersion shifted fibers

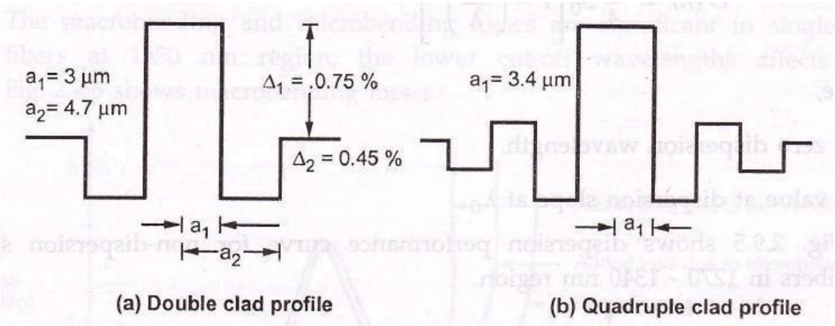
3. The addition of wavelength and material dispersion can shift the zero dispersion point of longer wavelength. Two configurations of dispersion shifted fibers are

Step index dispersion shifted fiber.

Triangular dispersion shifted fiber.

Dispersion Flattened

Dispersion flattened fibers are more complex to design. It offers much broader span of wavelengths to suit desirable characteristics. Two configurations are :



(a) Double clad profile (b) Quadruple clad profile

Fig. 2.9.3 Dispersion flattened

- Fig 2.9.4 shows total resultant dispersion.

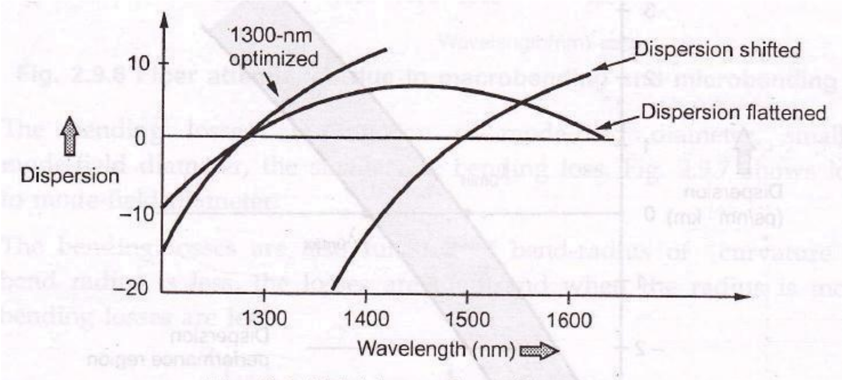


Fig. 2.9.4 Total resultant dispersion

Dispersion Calculations

- The total dispersion consists of material and waveguide dispersions. The resultant intermodal dispersion is given as,

$$D(\lambda) = \frac{d\tau}{d\lambda}$$

where, τ is group delay per unit length of fiber.

- The broadening σ of an optical pulse is given

$\sigma = D(\lambda) L\sigma \lambda$

where, σλ is half power spectral width of source.

- As the dispersion varies with wavelength and fiber type. Different formulae are used to calculate dispersions for variety of fiber at different wavelength.
- For a non – dispersion shifted fiber between 1270 nm to 1340 nm wavelength, the expression for dispersion is given as :

$$D(\lambda) = \frac{\lambda}{4} S_0 \left[1 - \left(\frac{\lambda_0}{\lambda}\right)^4\right]$$

where,

λ_0 is zero dispersion wavelength.

S_0 is value at dispersion slop at λ_0.

ιιι) Fig 2.9.5 shows dispersion performance curve for non-dispersion shifted fibers in 1270 – 1340 nm region.

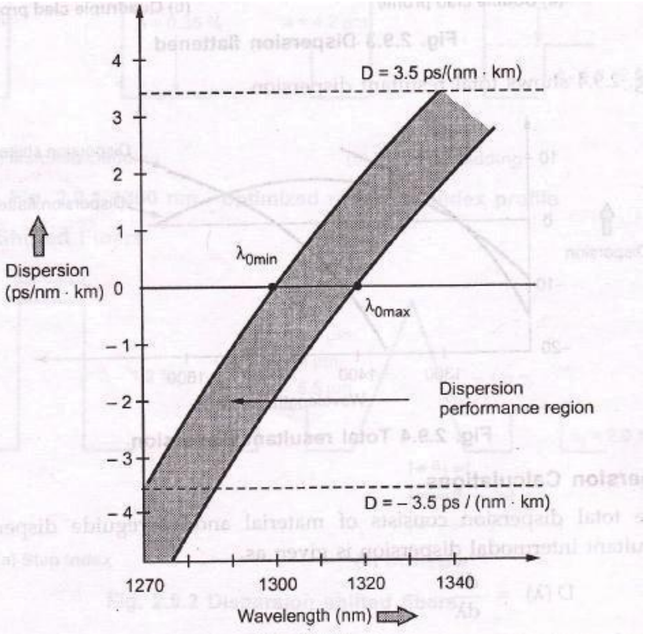

D = 3.5 ps/(nm · km)
4
3
2
1
0
– 1
– 2
– 3
– 4
Dispersion
(ps/nm · km)
λ_{0min}
λ_{0max}
Dispersion
performance region
D = – 3.5 ps / (nm · km)
1270
1300
1320
1340
Wavelength (nm)

Fig. 2.9.5

- Maximum dispersion specified as 3.5 ps/(nm . km) marked as dotted line in Fig. 2.9.5.

The cut-off frequency of an optical fiber

- The cut-off frequency of an optical fiber is determined not only by the fiber itself (modal dispersion in case of multimode fibers and waveguide dispersion in case of single mode fibers) but also by the amount of material dispersion caused by the spectral width of transmitter.

Bending Loss Limitations

- The macrobending and microbending losses are significant in single mode fibers at 1550 nm region, the lower cut-off wavelengths affects more. Fig. 2.9.6 shows macrobending losses.

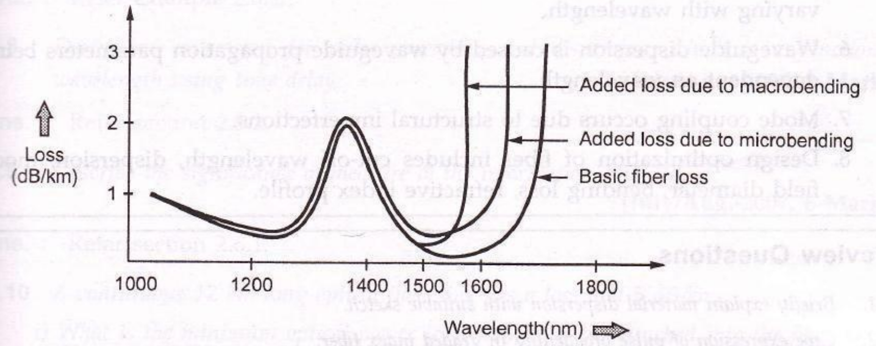


Fig. 2.9.6 Fiber attenuation due to macrobending and microbending

〈 The bending losses are function of mode-filed diameter, smaller the mode-field diameter, the smaller the bending loss. Fig. 2.9.7 shows loss due to mode-field diameter.

〈 The bending losses are also function of bend-radius of curvature. If the bend radius is less,

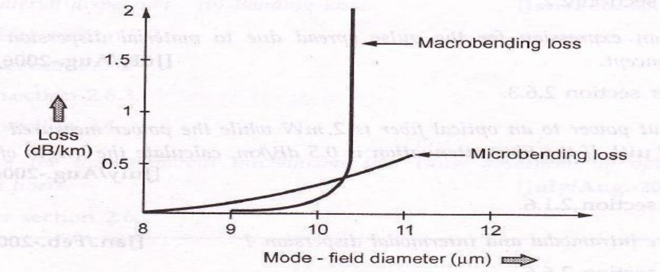


Fig. 2.9.7 Loss due to mode field diameter variation

the losses are more and when the radius is more, the bending losses are less.

Recommended Questions:

d) Briefly explain material dispersion with suitable sketch.

e) Give expression of pulse broadening in graded index fiber.

f) State the significance of mode coupling in optic fiber communication.

g) Explain in detail the design optimization of single mode fibers.

h) Elaborate dispersion mechanism in optical fibers.

UNIT - 3

OPTICAL DETECTORS

Optical Sources

3. Optical transmitter coverts electrical input signal into corresponding optical signal. The optical signal is then launched into the fiber. Optical source is the major component in an optical transmitter.

4. Popularly used optical transmitters are Light Emitting Diode (LED) and semiconductor Laser Diodes (LD).

Characteristics of Light Source of Communication

- To be useful in an optical link, a light source needs the following characteristics:

☐ It must be possible to operate the device continuously at a variety of temperatures for many years.

☐ It must be possible to modulate the light output over a wide range of modulating frequencies.

☐ For fiber links, the wavelength of the output should coincide with one of transmission windows for the fiber type used.

☐ To couple large amount of power into an optical fiber, the emitting area should be small.

☐ To reduce material dispersion in an optical fiber link, the output spectrum should be narrow.

- The power requirement for its operation must be low.

☐ The light source must be compatible with the modern solid state devices.

☐ The optical output power must be directly modulated by varying the input current to the device.

☐ Better linearity of prevent harmonics and intermodulation distortion. High

☐ coupling efficiency.

☐ High optical output power.

☐ High reliability.

☐ Low weight and low cost.

Two types of light sources used in fiber optics are light emitting diodes (LEDs) and laser diodes (LDs).

Light Emitting Diodes(LEDs) p-n Junction

Conventional p-n junction is called as **homojunction** as same semiconductor material is sued on both sides junction. The electron-hole recombination occurs in relatively

layer = 10 µm. As the carriers are not confined to the immediate vicinity of junction, hence high current densities can not be realized.

- The carrier confinement problem can be resolved by sandwiching a thin layer (= 0.1 µm) between p-type and n-type layers. The middle layer may or may not be doped. The carrier confinement occurs due to bandgap discontinuity of the junction. Such a junction is call **heterojunction** and the device is called double **heterostructure.**
- In any optical communication system when the requirements is –
  1. Bit rate f 100-2—Mb/sec.
  2. Optical power in tens of micro watts.

  LEDs are best suitable optical source.

LED Structures

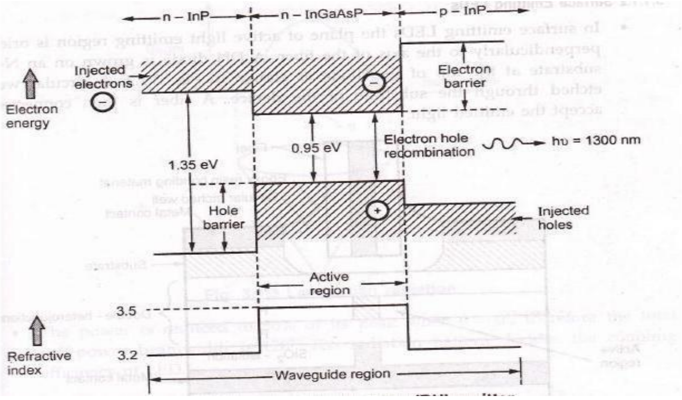
Heterojuncitons

- A heterojunction is an interface between two adjoining single crystal semiconductors with different bandgap.

- Heterojuctions are of two types, Isotype (n-n or p-p) or Antisotype (p-n).

Double Heterojunctions (DH)

In order to achieve efficient confinement of emitted radiation double **heterojunctions** are used in LED structure. A heterojunciton is a junction formed by dissimilar semiconductors. Double heterojunction (DH) is formed by two different semiconductors on each side of active region. Fig. 3.1.1 shows double heterojunction (DH) light emitter.



- The crosshatched regions represent the energy levels of freecharge. Recombination occurs only in active InGaAsP layer. The two materials have different bandgap energies and different refractive indices. The changes in bandgap energies create potential barrier for both holes and electrons. The free charges can recombine only in narrow, well defined active layer side.
- A double heterjuction (DH) structure will confine both hole and electrons to a narrow active layer. Under forward bias, there will be a large number of carriers injected into active region where they are efficiently confined. Carrier recombination occurs in small active region so leading to an efficient device. Antoer advantage DH structure is that the active region has a higher refractive index than the materials on either side, hence light emission occurs in an optical waveguide, which serves to narrow the output beam.

LED configurations

- At present there are two main types of LED used in optical fiber links –

  Surface emitting LED.
  Edge emitting LED.

  Both devices used a DH structure to constrain the carriers and the light to an active layer.

Surface Emitting LEDs

In surface emitting LEDs the plane of active light emitting region is oriented perpendicularly to the axis of the fiber. A DH diode is grown on an N-type substrate at the top of the diode as shown in Fig. 3.1.2. A circular well is etched through the substrate of the device. A fiber is then connected to accept the emitted

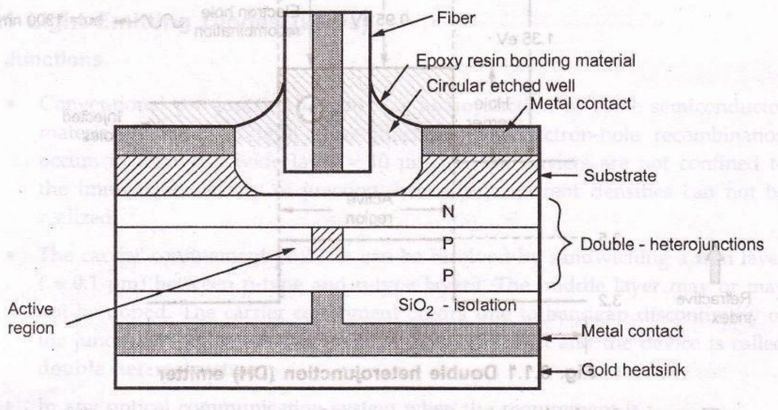


Fig. 3.1.2 Cross-section through a typical surface emitting LED

- At the back of device is a gold heat sink. The current flows through the p-type material and forms the small circular active region resulting in the intense beam of light. Diameter of circular active area = 50 µm

  Thickness of circular active area = 2.5 µm

  Current density = 2000 A/cm^2 half-power

  Emission pattern = Isotropic, 120^o beamwidth.

- The isotropic emission pattern from surface emitting LED is of Lambartian pattern. In Lambartian pattern, the emitting surface is uniformly bright, but its projected area diminishes as cos θ, where θ is the angle between the viewing direction and the normal to the surface as shown in Fig. 3.1.3. The beam intensity is maximum along the normal.

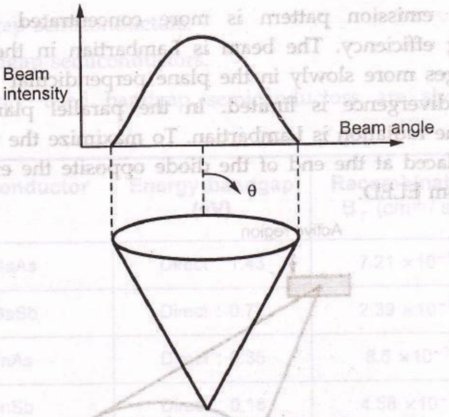


Fig. 3.1.3 Lambartian radiation

- The power is reduced to 50% of its peak when θ = 60^{o}, therefore the total half-power beamwidth is 120^{o}. The radiation pattern decides the coupling efficiency of LED.

Edge Emitting LEDS (ELEDs)

- In order to reduce the losses caused by absorption in the active layer and to make the beam more directional, the light is collected from the edge of the LED. Such a device is known as **edge emitting** LED or ELED.

It consists of an active junction region which is the source of incoherent light and two guiding layers. The refractive index of guiding layers is lower than active region but higher than outer surrounding material. Thus a waveguide channel is form and optical radiation is directed into the fiber. Fig.

shows structure of LED

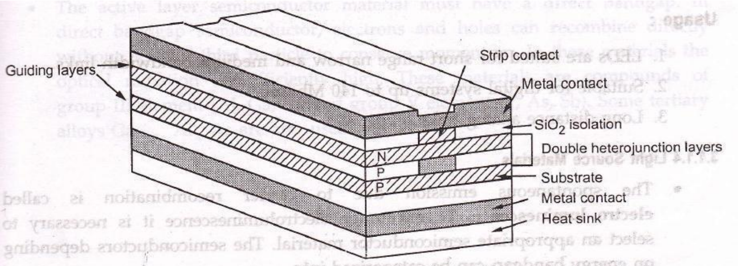


Fig. 3.1.4 Structure of edge emitting, DH, strip contact LED

Edge emitter’s emission pattern is more concentrated (directional) providing improved coupling efficiency. The beam is Lambartian in the plane parallel to the junction but diverges more slowly in the plane perpendicular to the junction. In this plane, the beam divergence is limited. In the parallel plane, there is no beam confinement and the radiation is Lambartian. To maximize the useful output power, a reflector may be placed at the end of the diode opposite the emitting edge. Fig. 3.1.5 shows radiation from ELED.

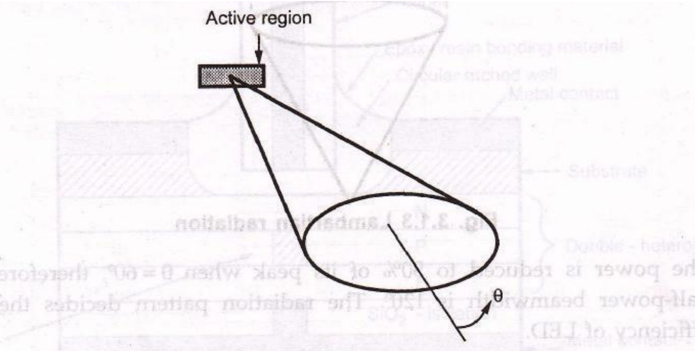


Fig. 3.1.5 Unsymmetric radiation from an edge emitting LED

Features of ELED:

- Linear relationship between optical output and current.
- Spectral width is 25 to 400 nm for λ = 0.8 – 0.9 µm.
- Modulation bandwidth is much large.

☐ Not affected by catastrophic gradation mechanisms hence are more reliable. ELEDs
☐ have better coupling efficiency than surface emitter.

☐ ELEDs are temperature sensitive.

Usage :

7. LEDs are suited for short range narrow and medium bandwidth links.
8. Suitable for digital systems up to 140 Mb/sec.
9. Long distance analog links

Light Source Materials

10. The spontaneous emission due to carrier recombination is called **electro luminescence**. To encourage electroluminescence it is necessary to select as appropriate semiconductor material. The semiconductors depending on energy bandgap can be categorized into,

    ☐ Direct bandgap semiconductors.
    ☐ Indirect bandgap semiconductors.

11. Some commonly used bandgap semiconductors are shown in following table 3.1.1

Semiconductor	Energy bandgap (eV)	Recombination B_r (cm^3 / sec)
GaAs	Direct : 1.43	7.21×10^{-10}
GaSb	Direct : 0.73	2.39×10^{-10}
InAs	Direct : 0.35	8.5×10^{-11}
InSb	Direct : 0.18	4.58×10^{-11}
Si	Indirect : 1.12	1.79×10^{-15}
Ge	Indirect : 0.67	5.25×10^{-14}
GaP	Indirect : 2.26	5.37×10^{-14}

Table 3.1.1 Semiconductor material for optical sources

15. Direct bandgap semiconductors are most useful for this purpose. In direct bandgap semiconductors the electrons and holes on either side of bandgap have same value of crystal momentum. Hence direct recombination is possible. The recombination occurs within 10^{-8} to 10^{-10} sec.

16. In indirect bandgap semiconductors, the maximum and minimum energies occur at

different values of crystal momentum. The recombination in these semiconductors is quite slow i.e. 10^{-2} and 10^{-3} sec.

The active layer semiconductor material must have a **direct bandgap**. In direct bandgap semiconductor, electrons and holes can recombine directly without need of third particle to conserve momentum. In these materials the optical radiation is sufficiently high. these

materials are compounds of group III elements (Al, Ga, In) and group V element (P, As, Sb). Some tertiary allos Ga_{1-x} Al_x As are also used.

5. Emission spectrum of Ga_{1-x} Al_xAs LED is shown in Fig. 3.1.6.

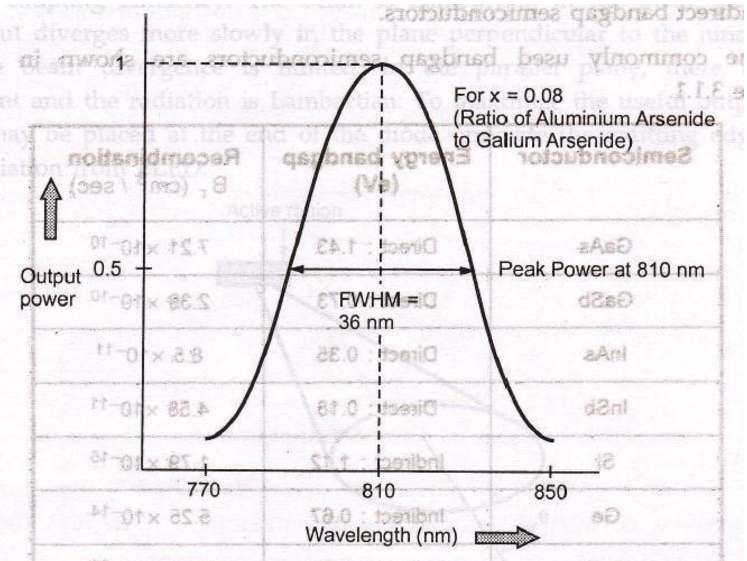


Fig. 3.1.6 Emission spectrum of Ga_{1-x} Al_x As LED

8. The peak output power is obtained at 810 nm. The width of emission spectrum at half power (0.5) is referred as full width half maximum (FWHM) spectral width. For the given LED FWHM is 36 nm.

9. The fundamental quantum mechanical relationship between gap energy E and frequency v is given as –

$$E = hv$$

$$E = h\frac{c}{\lambda}$$

$$\Rightarrow \qquad \lambda = \frac{hc}{E}$$

$$\boxed{\lambda(\mu m) = \frac{1.24}{E_g(eV)}}$$

where, energy (E) is in joules and wavelength (λ) is in meters. Expressing the gap energy (E_g) in electron volts and wavelength (λ) in micrometers for this application.

Different materials and alloys have different band gap energies

3. The bandgap energy (E_g) can be controlled by two compositional parameters x and y, within direct bandgap region. The quartenary alloy $In_{1-x}\ Ga_x\ As_y\ P_{1-y}$ is the principal material sued in such LEDs. Two expression relating E_g and x,y are –

$$\boxed{\begin{aligned} &E_g = 1.424 + 1.266\ x + 0266\ x^2 \qquad \ldots\ 3.1.3 \\ &E_g = 1.35 - 0.72\ y + 0.12\ y^2 \qquad \ldots\ 3.1.4 \end{aligned}}$$

Example 3.1.1 : Compute the emitted wavelength from an optical source having x = 0.07.

Solution : $x = 0.07$

$$\boxed{E_g = 1.424 + 1.266\ x + 0266\ x^2}$$

$$E_g = 1.424 + (1.266 \times 0.07) + 0266 \times (0.07)^2$$

$E_g = 1.513$ eV

Now

$$\boxed{\lambda = \frac{1.24}{E_g}}$$

$$\lambda = \frac{1.24}{1.513}$$

$$\lambda = 0.819\ \mu m$$

$$\lambda = 0.82\ \mu m$$

…Ans.

Example 3.1.2 : For an alloy $In_{0.74}\ Ga_{0.26}\ As_{0.57}\ P_{0.43}$ to be sued in Led. Find the wavelength emitted by this source.

Solution : Comparing the alloy with the quartenary alloy composition.

$In_{1-x}\ Ga_x\ As\ P_{1-y}$ it is found that

$x = 0.26$ and $y = 0.57$

$$\boxed{E_g = 1.35 - 0.72\,y + 0.12\,y^2}$$

Using

$E_g = 1.35-(0.72 \times 0.57) + 0.12 \times 0.57^2$ E_g =

0.978 eV

Now

$$\boxed{\lambda = \frac{1.24}{E_g}}$$

$$\lambda = \frac{1.24}{0.978}$$

$$\lambda = 1.2671\ \mu m$$

... Ans.

$$\lambda = \mathbf{1.27}\ \mu m$$

Quantum Efficiency and Power

- The internal quantum efficiency (η_{int}) is defined as the ratio of radiative recombination rate to the total recombination rate.

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}} \qquad \text{... 3.1.5}$$

Where,

R_r is radiative recombination rate.

R_{nr} is non-radiative recc

$$\eta_{int} = \frac{1}{1 + \frac{R_{nr}}{R_r}}$$

$$\frac{1}{\tau} =$$

If n are the excess carriers, then radiative life time, $\tau_r = \frac{n}{\mathrm{R_r}}$ and

non-radiative life time, $\tau_r = \frac{n}{\mathrm{R_{nr}}}$

The internal quantum efficiency is given

6 The recombination time of carriers in active region is τ. It is also known as bulk recombination life time.

… 3.1.7

Therefore internal quantum efficiency is given as –

$$\boxed{\eta_{int} = \frac{\tau}{\tau_r}} \qquad \text{... 3.1.8}$$

- If the current injected into the LED is I and q is electron charge then total number of recombinations per second is –

$R_r = R_{nr} = \frac{I}{q}$ From equation 3.1.5

$$\eta_{int} = \frac{R_r}{I / q}$$

∴

$$R_r = \eta_{int} \text{ x } \frac{I}{q} \qquad \text{... 3.1.9}$$

- Optical power generated internally in LED is given as –

$$P_{int} = R_r . h \, v$$

$$P_{int} = \left(\eta_{int} \text{ x } \frac{I}{q}\right) . h \, v$$

$$P_{int} = \left(\eta_{int} \text{ x } \frac{I}{q}\right) . h \frac{c}{\lambda}$$

∴

$$\boxed{P_{int} = \eta_{int} . \frac{hc \, I}{q\lambda}} \qquad \text{... 3.1.10}$$

Not all internally generated photons will available from output of device. The external quantum efficiency is used to calculate the emitted power. The external quantum

efficiency is defined as the ratio of photons emitted from LED to the number of photons generated internally. It is given by equation

$$\eta_{ext} = \frac{1}{n(n+1)^2} \qquad \text{… 3.1.11}$$

- The optical output power emitted from LED is given as –

$$P = \eta_{ext} . P_{int}$$

$$\boxed{P = \frac{1}{n\,(n+1)^2} . P_{int}}$$

Example 3.1.3 : The radiative and non radiative recombination life times of minority carriers in the active region of a double heterojunction LED are 60 nsec and 90 nsec respectively. Determine the total carrier recombination life time and optical power generated internally if the peak emission wavelength si 870 nm and the drive currect is 40 mA. **[July/Aug.-2006, 6 Marks]**

Solutions : Given : λ = 870 nm 0.87 x 10^{-6} m

τ_r = 60 nsec.

τ_{nr} = 90 nsec.

I = 40 mA = 0.04 Amp.

i) Total carrier recombination life time:

$$\boxed{\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}}$$

$$\frac{1}{\tau} = \frac{1}{60} + \frac{1}{90}$$

$$\frac{1}{\tau} = \frac{150}{5400}$$

$\therefore$ $\tau = 36$ **nsec.** **… Ans.**

ii) Internal optical power

$$P_{int} = \eta_{int} \cdot \frac{hc\,I}{q\lambda}$$

$$P_{int} = \left(\frac{\tau}{\tau_r}\right)\left(\frac{hc\,I}{q\lambda}\right)$$

$$P_{int} = \left(\frac{30}{60}\right)\left[\frac{(6.625 \times 10^{-34})(3 \times 10^{8}) \times 0.04}{(1.602 \times 10^{-19})(0.87 \times 10^{-6})}\right]$$

$$P_{int} = 34.22 \text{ mW}$$

Example 3.1.4 : A double heterjunciton InGaAsP LED operating at 1310 nm has radiative and non-radiative recombination times of 30 and 100 ns respectively. The current injected is 40 Ma. Calculate –

- ☐ Bulk recombination life time.
- ☐ Internal quantum efficiency.
- ☐ Internal power level.

Solution : $\lambda = 1310 \text{ nm} = (1.31 \times 10^{-6} \text{ m})$

$\tau_r = 30$ ns

$\tau_{nr} = 100$ ns

I = 40 MA – 0.04 Amp.

☐ $$\boxed{\eta_{int} = \frac{\tau}{\tau_r}}$$

Bulk Recombination Life time (τ) :

$$\boxed{\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}}$$

∴ $\tau = 23.07$ **nsec.** **… Ans.**

$$P_{int} = \eta_{int} \cdot \frac{hc\,I}{q\lambda}$$

☐ **Internal euqntum efficienty (η_{int})**

$$\eta_{int} = \frac{23.07}{30}$$

$$\eta_{int} = \mathbf{0.769}$$

... Ans.

iii) Internal pwer level (P_{int}) :

Advantages and Disadvantages of LED

Advantages of LED

☐ Simple design.
☐ Ease of manufacture. Simple
☐ system integration. Low
☐ cost.
☐ High reliability.

Disadvantages of LED

☐ Refraction of light at semiconductor/air interface.

☐ The average life time of a radiative recombination is only a few nanoseconds, therefore nodulation BW is limited to only few hundred megahertz.

☐ Low coupling efficiency. Large
☐ chromatic dispersion.

Comparison of Surface and Edge Emitting LED

LED type	Maximum modulation frequency (MHz)	Output power (mW)	Fiber coupled power (mW)
Surface emitting	60	< 4	< 0.2
Edge emitting	200	< 7	< 1.0

Injection Laser Diode (ILD)

- The laser is a device which amplifies the light, hence the LASER is an acronym for light amplification by stimulated emission of radiation.

The operation of the device may be described by the formation of an electromagnetic standing wave within a cavity (optical resonator) which provides an output of monochromatic highly coherent radiation.

Principle :

Material absorb light than emitting. Three different fundamental process occurs between the two energy states of an atom.

Absorption 2) Spontaneous emission 3) Stimulated emission.

- Laser action is the result of three process absorption of energy packets (photons) spontaneous emission, and stimulated emission. (These processes are represented by the simple two-energy-level diagrams).

  Where E_1 is the lower state energy level.

  E_2 is the higher state energy level.

- Quantum theory states that any atom exists only in certain discrete energy state, absorption or emission of light causes them to make a transition from one state to another. The frequency of the absorbed or emitted radiation f is related to the difference in energy E between the two states.

  If E_1 is lower state energy level. and
  E_2 is higher state energy level. $E = (E_2 - E_1) = h.f.$

  Where, $h = 6.626 \times 10^{-34}$ J/s (Plank's constant).

- An atom is initially in the lower energy state, when the photon with energy $(E_2 - E_1)$ is incident on the atom it will be excited into the higher energy state E_2 through the absorption of the photon

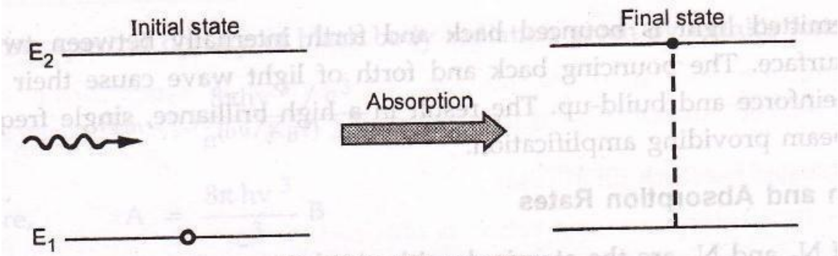


Fig. 3.1.7 Absorption

- When the atom is initially in the higher energy state E_2, it can make a transition to the lower energy state E_1 providing the emission of a photon at a frequency corresponding to $E = h.f.$ The emission process can occur in two ways.

By spontaneous emission in which the atom returns to the lower energy state in random manner.

By stimulated emission when a photon having equal energy to the difference between

the two states (E2 – E1) interacts with the atom causing it to the lower state with the creation of the second photon

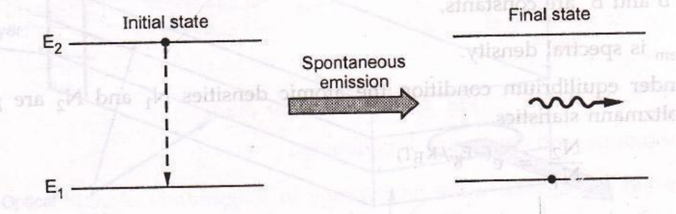


Fig. 3.1.8 Spontaneous emission

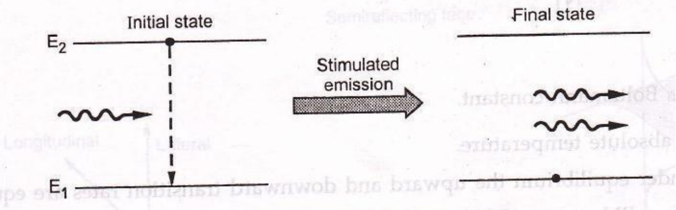


Fig. 3.1.9 Stimulated emission

- Spontaneous emission gives incoherent radiation while stimulated emission gives coherent radiation. Hence the light associated with emitted photon is of same frequency of incident photon, and in same phase with same polarization.
- It means that when an atom is stimulated to emit light energy by an incident wave, the liberated energy can add to the wave in constructive manner. The emitted light is bounced back and forth internally between two reflecting surface. The bouncing back and forth of light wave cause their intensity to reinforce and build-up. The result in a high brilliance, single frequency light beam providing amplification.

Emission and Absorption Rates

3. It N_1 and N_2 are the atomic densities in the ground and excited states.

Rate of spontaneous emission

$$R_{spon} = AN_2 \qquad \ldots\ 3.1.13$$

Rate of stimulated emission

$$R_{stim} = BN_2 \rho_{em} \qquad \ldots\ 3.1.14$$

Rate of absorption

$$R_{abs} = B' N_1 \rho_{em} \qquad \ldots\ 3.1.15$$

where,

A, B and B’ are constants.

ρ_{em} is spectral density.

- Under equilibrium condition the atomic densities N_1 and N_2 are given by Boltzmann statistics.

$$\frac{N_2}{N_1} = eg^{(-E_B / K_B T)} \qquad \text{… 3.1.16}$$

$$\frac{N_2}{N_1} = eg^{(-h_v / K_B T)} \qquad \text{… 3.1.17}$$

where,

K_B is Boltzmann constant. T

is absolute temperature.

- Under equilibrium the upward and downward transition rates are equal.

$$AN_2 + BN_2\, \rho_{em} = B'\, N_1\, \rho_{em} \qquad \text{… 3.1.18}$$

Spectral density ρ_{em}

… 3.1.19

Comparing spectral density of black body radiation given by Plank’s formula,

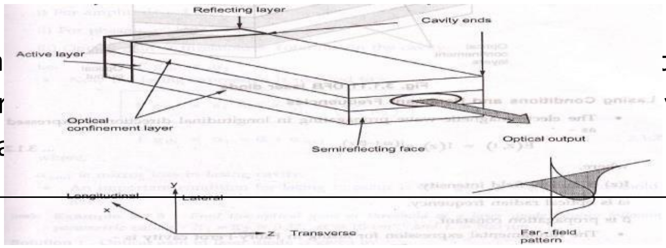
… 3.1.20

Therefore, … 3.1.21

- A and B are called Einstein’s coefficient.

Fabry – Perot Resonator

- Lasers a or is formed by a resonant cavity pr y a Fabry-Perot resonator i.e. two para



Light propagating along the axis of the interferometer is reflected by the mirrors back to the amplifying medium providing optical gain. The dimensions of cavity are 25-500 µm longitudinal 5-15 µm lateral and 0.1-0.2 µm transverse. Fig. 3.1.10 shows Fabry-Perot resonator cavity for a laser diode.

- The two heterojunctions provide carrier and optical confinement in a direction normal to the junction. The current at which lasing starts is the threshold current. Above this current the output power increases sharply.

Distributed Feedback (DFB) Laser

In DFB laster the lasing action is obtained by periodic variations of refractive index along the longitudinal dimension of the diode. Fig. 3.1.11 shows the structure of DFB laser diode

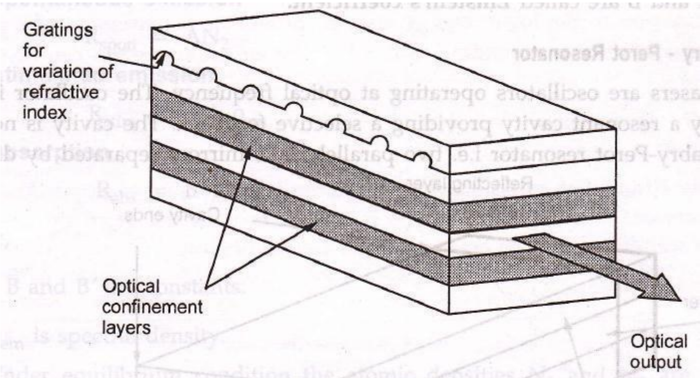


Fig. 3.1.11 DFB laser diode

Lasing conditions and resonant Frequencies

- The electromagnetic wave propagating in longitudinal direction is expressed as –

$$E(z, t) = I(z)\, e^{j(\omega t - \beta z)} \qquad \ldots 3.1.23$$

where,

I(z) is optical field intensity.

□ is optical radian frequency. β is propagation constant.

The fundamental expression for lasing in Fabry-Perot cavity is –

$$I(z) = I(0)e^{[\{\Gamma g(h\nu)-\alpha(h\nu)\}z]}$$

… 3.1.24

where,

□is optical field confinement factor or the fraction of optical power in the active layer. α is effective absorption coefficient of material.

g is gain coefficient.

h v is photon energy.

z is distance traverses along the lasing cavity.

The condition of lasing threshold is given as –

- For amplitude : I (2L) = I (0) For
- phase : $e\text{-}j^{2\beta L} = 1$
- Optical gain at threshold = Total loss in the cavity.

i.e. $\Gamma g_{th} = \alpha_t$

- Now the lasing expression is reduced to –

$$\boxed{\Gamma g_{th} = a_t = \alpha + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)}$$

… 3.1.26

… 3.1.27

$$\Gamma g_{th} = \propto_t = \propto + \propto_{end}$$

where,

A_{end} is mirror loss in lasing cavity.

- An important condition for lasing to occur is that gain, $g \geq g_{th}$ i.e. threshold gain.

Example 3.1.5 : Find the optical gain at threshold of a laser diode having following parametric values – $R_1 = R_2 = 0.32$, $\alpha = 10\text{cm}^{-1}$ and $L = 500\ \mu\text{m}$.

Solution : Optical gain in laser diode is given by –

$$\Gamma g_{th} = 10 + \frac{1}{2 \text{ x } (500 \text{ x } 10^{-4})} \ln\left(\frac{1}{0.32 \text{ x } 0.32}\right)$$

$$\boldsymbol{\Gamma g_{th} = 33.7 \text{ cm}^{-1}}$$

... Ans.

Power Current Characteristics

The output optic power versus forward input current characteristics is plotted in Fig. 3.1.12 for a typical laser diode. Below the threshold current (I_{th}) only spontaneous emission is emitted hence there is small increase in optic power with drive current. at threshold when lasing conditions are satisfied. The optical power increases sharply after the lasing threshold because of stimulated emission.

- The lasing threshold optical gain (g_{th}) is related by threshold current density (J_{th}) for stimulated emission by expression –

$$g_{th} = \beta J_{th} \qquad \text{... 3.1.28}$$

where, β is constant for device structure.

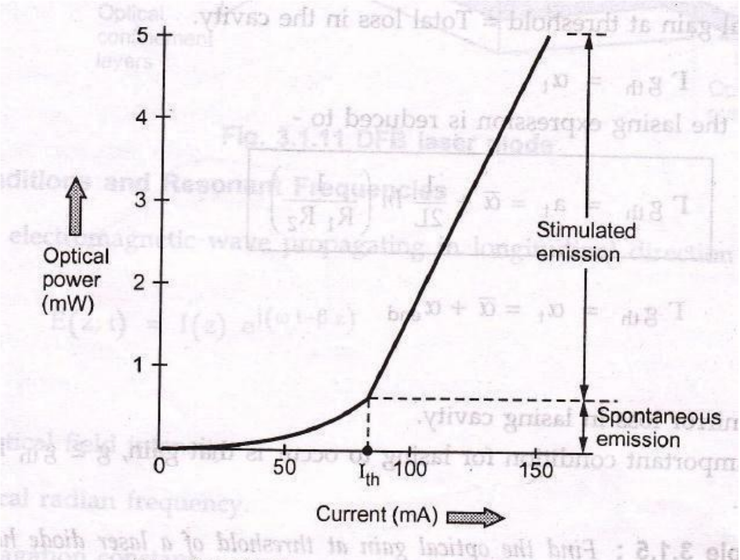


Fig. 3.1.12 Power current characteristics

Fig. 3.1.12 Power current characteristics

External Quantum Efficiency

- The external quantum efficiency is defined as the number of photons emitted per electron hole pair recombination above threshold point. The external quantum efficiency η_{ext} is given by –

$$\eta_{ext} = \frac{\eta_i (g_{th} - \alpha)}{g_{th}}$$

... 3.1.29

where,

η_i = Internal quantum efficiency (0.6-0.7). g_{th} =

Threshold gain.

α = Absorption coefficient

- Typical value of η_{ext} for standard semiconductor laser is ranging between 15-20 %.

Resonant Frequencies

- At threshold lasing

$2\beta L = 2\pi m$

where, $\beta = \frac{2\pi m}{\lambda}$ (propagation constant)

m is an integer.

$\therefore$ $m = 2L.\frac{n}{\lambda}$ ...3.1.30

Since $c = v\lambda$

∴ $\lambda = \frac{c}{v}$

Substituting λ in 3.1.30

$$m = 2L\,\frac{nv}{c} \qquad \text{=z... 3.1.31}$$

- Gain in any laser is a function of frequency. For a Gaussian output the gain and frequency are related by expression –

$$g(\lambda) = g(0)e^{\left[-\frac{(\lambda-\lambda_0)^2}{2\sigma^2}\right]} \quad \text{… 3.1.32}$$

where,

g(0) is maximum gain.

λ_0 is center wavelength in spectrum.

□ is spectral width of the gain.The frequency spacing between the two successive modes is –

$$\boxed{\Delta v = \frac{c}{2Ln}}$$

$$\boxed{\Delta \lambda = \frac{\lambda^2}{2Ln}}$$

… 3.1.34

Optical Characteristics of LED and Laser

- The output of laser diode depends on the drive current passing through it. At low drive current, the laser operates as an inefficient Led, When drive current crosses threshold value, lasing action beings. Fig. 3.1.13 illustrates graph comparing optical powers of LED operation (due to spontaneous emission) and laser operation (due to stimulated emission).

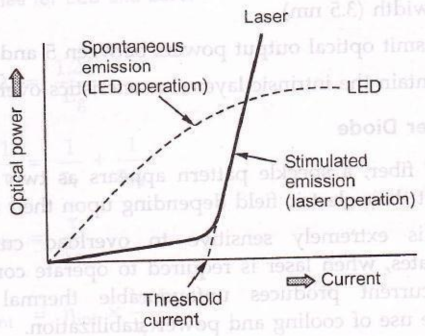


Fig. 3.1.13 Optical characteristics of an LED and laser compared

Spectral and Spatial Distribution of Led and Laser

At low current laser diode acts like normal LED above threshold current, stimulated emission i.e. narrowing of light ray to a few spectral lines instead of broad spectral distribution, exist. This enables the laser to easily couple to single mode fiber and reduces the amount of uncoupled light (i.e. spatial radiation distribution). Fig. 3.1.14 shows spectral and spatial distribution difference between two diodes

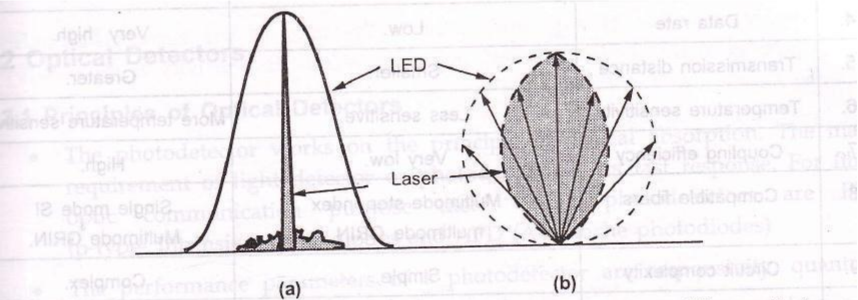


Fig. 3.1.14 Comparing (a) spectral and (b) spatial distribution of laser diodes

Advantages and Disadvantages of Laser Diode

Advantages of Laser Diode

- Simple economic design.
- High optical power.
- Production of light can be precisely controlled. Can be used at high temperatures.
- Better modulation capability.
- High coupling efficiency.
- Low spectral width (3.5 nm)
- Ability to transmit optical output powers between 5 and 10 mW. Ability to maintain the intrinsic layer characteristics over long periods.

Disadvantages of Laser Diode

- At the end of fiber, a speckle pattern appears as two coherent light beams add or subtract their electric field depending upon their relative phases.
- Laser diode is extremely sensitive to overload currents and at high transmission rates, when laser is required to operate continuously the use of large drive current produces unfavourable thermal characteristics and necessitates the use of cooling and power stabilization.

Comparison of LED and Laser Diode

Sr. No.	Parameter	LED	LD (Laser Diode)
1.	Principle of operation	Spontaneous emission.	Stimulated emission.
2.	Output beam	Non – coherent.	Coherent.

3.	Spectral width	Board spectrum (20 nm – 100 nm)	Much narrower (1-5 nm).

4.	Data rate	Low.	Very high.
5.	Transmission distance	Smaller.	Greater.
6.	Temperature sensitivity	Less sensitive.	More temperature sensitive.
7.	Coupling efficiency	Very low.	High.

8.	Compatible fibers	Multimode step index multimode GRIN.	Single mode Sl Multimode GRIN.
9.	Circuit complexity	Simple	Complex
10.	Life time	10^5 hours.	10^4 hours.
11.	Cost	Low.	High.
12.	Output power	Linearly proportional to drive current.	Proportional to current above threshold.
13.	Current required	Drive current 50 to 100 mA peak.	Threshold current 5 to 40 mA.
14.	Wavelengths available	0.66 to 1.65 µm.	0.78 to 1.65 µm.
15.	Applications	Moderate distance low data rate.	Long distance high data rates.

Important Formulae for LED and Laser

LED

1. $\lambda = \frac{1.24}{E_g}$

   $\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$
2. $\eta_{int} = \frac{\tau}{\tau_r}$
3. $P_{int} = \eta_{int} \times \frac{hc\,I}{q\lambda}$
4.

LASER

1. $\Gamma g_{th} = \alpha + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$

   $\Delta v = \frac{c}{}$

2.

3.

Optical Detectors

Principles of Optical Detectors

- The photodetector works on the principle of optical absorption. The main requirement of light detector or photodector is its fast response. For fiber optic communication purpose most suited photodetectors are PIN (p-type- Instrinsic-n-type) diodes and APD (Avalanche photodiodes)
- The performance parameters of a photodetector are responsivity, quantum efficiency, response time and dark current.

Cut-off Wavelength (λ_C)

- Any particular semiconductor can absorb photon over a limited wavelength range. The highest wavelength is known as cut-off wavelength (λ_C). The cut-off wavelength is determined by bandgap energy E_g of material.

$$\boxed{\lambda_c = \frac{hc}{E_g} = \frac{1.24}{E_g}} \quad \dots 3.2.1$$

where,

E_g inelectron volts (eV) and

λ_C cut-off wavelength is in µm.

Typical value of λ_C for silicon is 1.06 µm and for germanium it is 1.6 µm.

Quantum Efficiency (η)

- The quantum efficiency is define as the number of electron-hole carrier pair generated per incident photon of energy h v and is given as –

$$\eta = \frac{\text{Number of electron hole pairs generated}}{\text{Number of incident photons}}$$

$$\eta = \frac{I_p / q}{P_{in} / h\,v} \qquad \text{... 3.2.2}$$

where, I_p is average photocurrent.

P_{in} is average optical power incident on photo detectors.

- Absorption coefficient of material determines the quantum efficiency. Quantum efficiency η < 1 as all the photons incident will not generate e-h pairs. It is normally expressed in percentage.

Fiber Alignment

5. In any fiber optic communication system, in order to increase fiber length there is need to joint the length of fiber. The interconnection of fiber causes some loss of optical power. Different techniques are used to interconnect fibers. A permanent joint of cable is referred to as **splice** and a temporary joint can be done with the connector.

6. The fraction of energy coupled from one fiber to other proportional to common mode volume M_{common}. The fiber – to – fiber coupling efficiency is given as –

$$\eta_F = \frac{M_{common}}{M_E}$$

where,

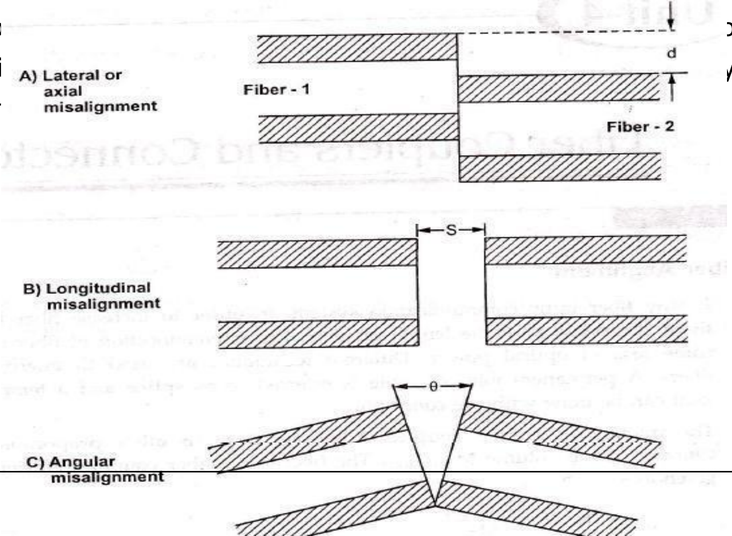
M_E is number of modes in fiber which launches power into next fiber.

- The fiber – to – fiber coupling loss L_F is given as –

$$L_F = -10\log \eta_F$$

Mechanical Misalignment

The diameter of fiber is few micrometer hence the microscopic alignment is required. If the radiation cone of emitting fiber do on loss takes place. The magnitude of radiati ypes of mechanical misalignments are showr



Lateral misalignment

Lateral or axial misalignment occurs when the axes of two fibers are separated by distance ‘d’.

Longitudinal misalignment

Longitudinal misalignment occurs when fibers have same axes but their end faces are separated by distance ‘S’.

Angular misalignment

Angular misalignment occurs when fiber axes and fiber end faces are no longer parallel. There is an angle ‘θ’ between fiber end faces.

The axial or lateral misalignment is most common in practice causing considerable power loss. The axial offset reduces the common core area of two fiber end faces as shown in

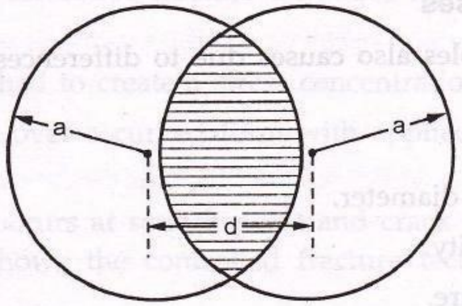


Fig. 4.1.2 Axial offset of fibers

- The optical power coupled is proportional to common area of two fiber cores. The common area is given by expression –

$$A_{\text{common}} = 2a^2 \text{ across} \frac{d}{2a} - d\left(a^2 - \frac{d^2}{n}\right)^{1/2} \qquad \dots (4.1.3)$$

where,

a is core radius of fiber.

d is separation of core axes.

- The coupling efficiency for step index fiber is the ratio of common core area to the end- face area.

$$\eta_{step} = \frac{A_{common}}{\pi a^2}$$

$$\eta_{step} = \frac{2}{\pi}\ \mathrm{across}\frac{d}{2a} - \frac{d}{\pi a}\left[1 - \left(\frac{d}{2a}\right)^2\right]^{1/2}$$

- For graded index fiber, the total received power for axial misalignment is given by –

.1.5)

$$P_T = \frac{2}{\pi}P\left\{\mathrm{across}\frac{d}{2a} - \left[1 - \left(\frac{d}{2a}\right)^2\right]^{1/2}\ \frac{d}{6a}\left(5 - \frac{d^2}{2a^2}\right)\right\}$$

where,

P is the power in emitting fiber.

When, d << a, the above expression reduces … (4.1.6)

Fiber Related Losses

- Losses in fiber cables also causes due to differences in geometrical and fiber characteristics.

  These includes,

  1) Variation in core diameter.
  2) Core area ellipticity.
  3) Numerical aperture.
  4) Refractive – index profile.
  5) Core-cladding concentricity.

  The user have less control over these variations since they are related to manufacturing process.

- Coupling loss when emitter fiber radius a_E and receiving fiber radius a_R is not same, is given as –

$$L_F(a) = \begin{cases} -10 \log \left(\frac{a_R}{a_E}\right)^2 & for\ a_R < a_E \\ 0 & for\ a_R \geq a_E \end{cases} \tag{4.1.7}$$

where,

a_E is emitter fiber radius. a_R

is receiver fiber radius.

- Coupling loss when numerical apertures of two fibers are not equal, to expressed as –

$$L_F(NA) = \begin{cases} -10 \log \left[\frac{NA_R\ (0)}{NA_E\ (0)}\right]^2, & for\ NA_R < NA_E \\ 0, & for\ NA_R \geq NA_E \end{cases} \tag{4.1.8}$$

- Coupling loss when core refractive index of two fibers are not same, is expressed as

$$L_F(\propto) = \begin{cases} -10 \log \frac{\propto_R\ (\propto_E + 2)}{\propto_E\ (\propto_R + 2)}, & for\ \propto_R < \propto_E \\ 0, & for\ \propto_R \geq \propto_E \end{cases} \tag{4.1.9}$$

Fiber Splices

- A permanent or semipermanent connection between two individual optical fibers is known as **fiber splice**. And the process of joining two fibers is called as **splicing**.
- Typically, a splice is used outside the buildings and connectors are used to join the cables within the buildings. Splices offer lower attenuation and lower back reflection than connectors and are less expensive.

Types of Splicing

- There are two main types of splicing

Fusion splicing.

Mechanical splicing / V groove

Fusion Splicing

10. Fusion splicing involves butting two cleaned fiber end faces and heating them until they melt together or fuse.
11. Fusion splicing is normally done with a fusion splicer that controls the alignment of the two fibers to keep losses as low as 0.05 dB.

6. Fiber ends are first prealigned and butted together under a microscope with micromanipulators. The butted joint is heated with electric arc or laser pulse to melt the fiber ends so can be bonded together. Fig. 4.2.1 shows fusion splicing of optical fiber

Mechanical Splicing / V Groove

12. Mechanical splices join two fibers together by clamping them with a structure or by epoxying the fibers together.
13. Mechanical splices may have a slightly higher loss and back reflection. These can be reduced by inserting index matching gel.
14. V groove mechanical splicing provides a temporary joint i.e fibers can be disassembled if required. The fiber ends are butted together in a V – shaped groove as shown in Fig..

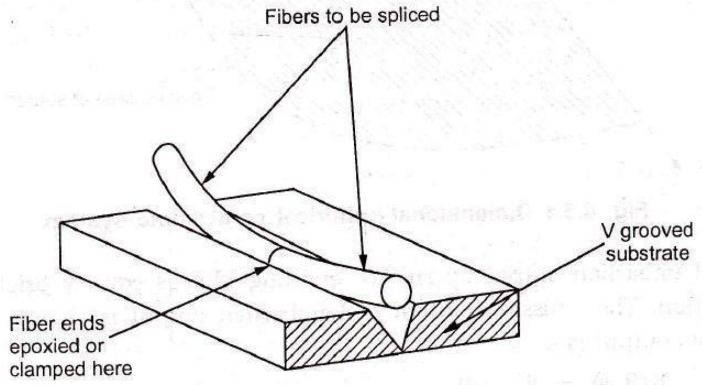


Fig. 4.2.2 V groove optical fiber splicing technique

17. The splice loss depends on fiber size and eccentricity.

Source-to-Fiber Power Launching

Optical output from a source is measured in radiance (B). Radiance is defined as the optical power radiated into a solid angle per unit emitting surface area. Radiance is specified in Watts/cm^2/Steradian. Radiance is important for defining source to fiber coupling efficiency.

Source Output Pattern

10. Spatial radiation pattern of source helps to determine the power accepting capability of fiber.
11. Fig. 4.3.1 shows three dimensional spherical co-ordinate system for characterizing the emission pattern from an optical source. Where the polar axis is normal to the emitting surface and radiance is a function of θ and ϕ.

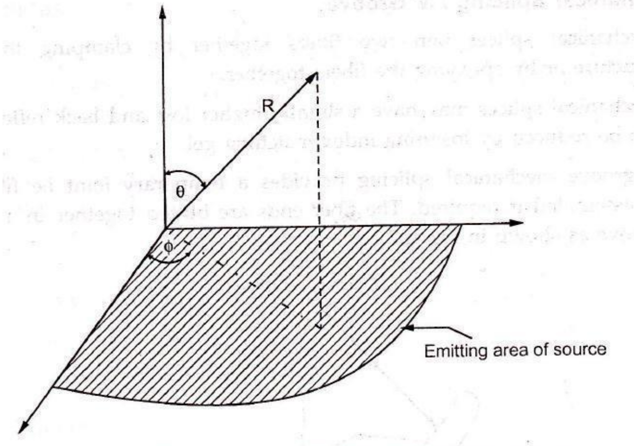


Fig. 4.3.1 Dimensional spherical co-ordinate system

4. The Lambartian output by surface emitting LED is equally bright from any direction. The emission pattern of Lambartian output is shown in Fig. 4.3.2 and its output is –

$$B(\theta,\phi) = B_0 \cos\theta$$

where, B_0 is the radiance along the normal to the radiating surface.

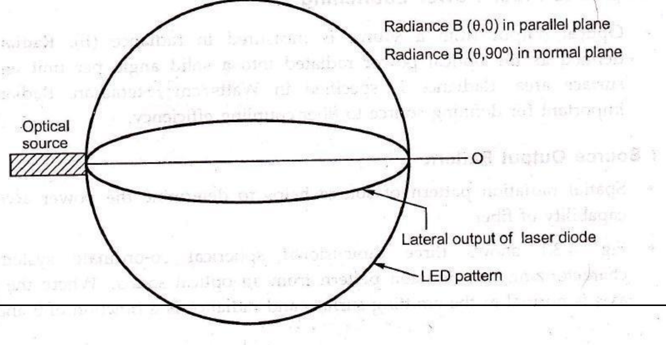


Fig. 4.3.2 Radiance pattern of Lambartian source

- Both radiations in parallel and normal to the emitting plane are approximated by expression –

$$\frac{1}{B(\theta,\phi)} = \frac{\sin^2\phi}{B_0 \cos^T\theta} + \frac{\cos^2\phi}{B_0 \cos^L\theta} \qquad \dots (4.3.2)$$

where,

T and L are transverse and lateral power distribution coefficients.

Power Coupling Calculation

- To calculate power coupling into the fiber, consider an optical source launched into the fiber as shown in Fig. 4.3.3.

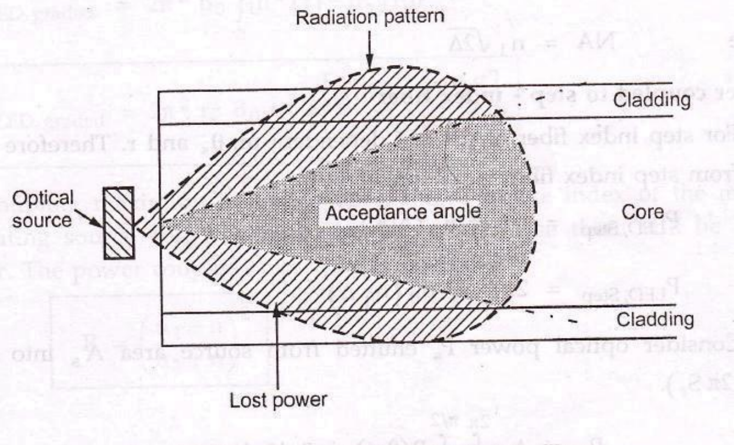


Fig. 4.3.3 Optical source coupled to fiber

Brightness of source is expressed as $B(A_S, \Omega_S)$,

Where, A_S is area of source

Ω_S is solid emission angle of source.

The coupled power P can be calculated as –

$$\mathrm{P} = \int_{\mathrm{A_f}} \mathrm{d\,A_s} \int_{\Omega_2} \mathrm{d}\Omega_s \ \mathrm{B}(\mathrm{A_s}\Omega_s)$$

$$\mathrm{P} = \int_0^r \int_0^{2\pi} \left[\int_0^{2\pi^{\phi}} \int_0^{0_{\max}} \mathrm{B}(\theta,\phi) \sin\theta \, d\theta \, d\phi \right] d\theta_s \, r dr \qquad \dots (4.3.3)$$

The integral limits are area of source and solid acceptance angle (θ_{0max}).

Here $d\theta_s$ rdr is incremental emitting area.

- Let the radius of surface emitting LED is rs, and for Lambartian emitter, $B(\theta,\phi) = B_0 \cos\theta$, then

$$P = \int_0^r \int_0^{2\pi} \left(2\pi B_0 \int_0^{0max} \cos\theta \sin\theta \, d\theta\right) d\theta_s \, rdr$$

$$P = B_0 . \pi \int_0^{r_s} \int_0^{2\pi} \sin^2\theta \; 0_{max} \, d\theta_s \, rdr$$

$$P = B_0 . \pi \int_0^{r_s} \int_0^{2\pi} NA^2 \, d\theta_s \, rdr \qquad \ldots (4.3.4)$$

Since $$NA = n_1\sqrt{2\Delta}$$

Power coupled to step – index fiver

- For step index fiber NA is not dependent on θ_s and r. Therefore LED power from step index fiber is,

$$P_{LED}, \text{Step} = \pi^2 r_s^2 B_0 (NA)^2$$

$$P_{LED}, \text{Step} = 2\pi^2 r_s^2 B_0 \left(n_1^2 \, \Delta\right) \qquad \ldots (4.3.5)$$

- Consider optical power P_s emitted from source are A_s into hemisphere(2π S_r).

$$P = A_s \int_0^{2\pi} \int_0^{\pi/2} B(\theta,\phi) \sin\theta \, d\theta \, d\phi$$

$$P = \pi \, r_s^2 2\pi B_o \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta$$

- When source radius r_S <a, the fiber core radius, the LED output power is given from equation (4.3.5).

$$P_s, \text{Step} = P_s (\text{NA})^2 \qquad \dots (4.3.7)$$

- When r_S > a equation (4.3.5) becomes,

$$\boxed{P_{\text{LED}}, \text{Step} = \left(\frac{a}{r_s}\right)^2 . P_s \, (\text{NA})^2} \qquad \dots (4.3.8)$$

Power coupled to graded index fiber

- In graded index fiber, the index of refraction varies radially from fiber axis. Numerical aperture for graded index fiber is given by,

$$P_{LED}, \text{Step} = 2\pi^2 B_0 \int_0^{r_s} \left[n^2(r) - n_2^2\right] r\,dr$$

Is source radius (r_S) is less than fiber core radius (a) i.e. $r_S < a$, the power coupled from surface emitting LED is given as –

$$\boxed{P_{LED}, \text{Step} = 2\pi^2 r_s^2 B_0 n_1^2 \Delta \left[1 - \frac{2}{\alpha+2}\left(\frac{r_s}{a}\right)^{\alpha}\right]}$$

- For coupling maximum power to fiber, the refractive index of the medium separating source and fiber must be same, otherwise there will be loss of power. The power couple is reduced by factor,

$$R = \left(\frac{n_1 - n}{n_1 + n}\right)^2$$

where,

n is the refractive index of medium.

n_1 is the refractive index of fiber core. R is the Fresnel reflection or reflectivity

Lensing Schemes for Coupling Improvement

- When When the emitting area of the source is smaller than the core area of fiber, the power coupling efficiency becomes poor. In order to improve the coupling efficiency miniature lens is placed between source and fiber. Microlens magnifies the emitting area of source equal to core area. The power coupled increases by a factor equal to magnification factor of lens.

- Important types of lensing schemes are

  : Rounded – end fiber.
  Spherical – surfaced LED and Spherical-ended fiber.
  Taper ended fiber.

  Non imaging microsphere.
  Cylindrical lens,

  Imaging sphere.

- There are some drawbacks of using lens.

Complexity increases.

Fabrication and handling difficulty.

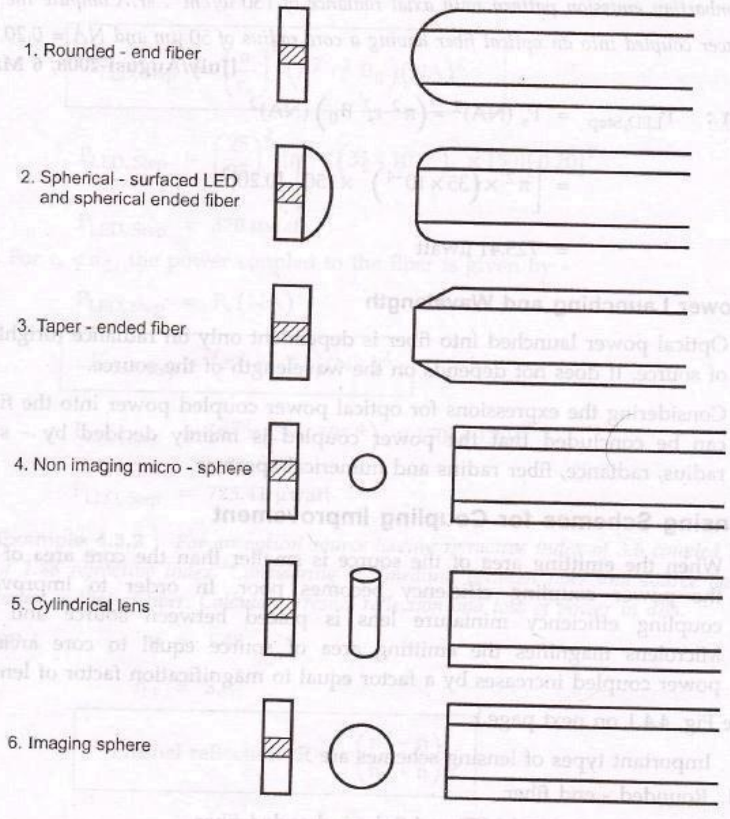


Fig. 4.4.1 Lensing schemes

UNIT-IV

OPTICAL AMPLIFIERS

Detector Responsivity ($\Re$)

- The responsivity of a photodetector is the ratio of the current output in amperes to the incident optical power in watts. Responsivity is denoted by $\Re$.

$$\Re = \frac{I_p}{P_{in}} \qquad \dots 3.2.3$$

But

$$\eta = \frac{I_p - q}{P_{in} - h\,v} = \frac{I_p}{q}\,\frac{h\,v}{P_{in}}$$

∴

$$\frac{I_p}{P_{in}} = \frac{\eta\,q}{h\,v} \qquad \dots 3.2.4$$

Therefore

$$\boxed{\Re = \frac{\eta\,q}{h\,v} = \frac{\eta\,q^{\lambda}}{h\,v}} \qquad \therefore v = \frac{c}{\lambda} \qquad \dots 3.2.5$$

- Responsivity gives transfer characteristics of detector i.e. photo current per unit incident optical power.
- Typical responsivities of pin photodiodes are –
  Silicon pin photodiode at 900 nm →0.65 A/W.
  Germanium pin photodiode at 1.3 μm →0.45 A/W. In GaAs pin photodiode at 1.3 μm →0.9 A/W.

$$\eta = \frac{5.4 \times 10^6}{6 \times 10^6}$$

$$\eta = 0.9 = \mathbf{90}\ \% \qquad \textbf{... Ans.}$$

- r photodetectors are sued. As the intensity of optical signal at the receiver is very low, the detector has to meet high performance specifications.

The conversion efficiency must be high at the operating wavelength. The speed of response must be high enough to ensure that signal distortion does not occur

The detection process introduce the minimum amount of noise.

It must be possible to operate continuously over a wide range of temperatures for many years.

The detector size must be compatible with the fiber dimensions.

4. At present, these requirements are met by reverse biased p-n photodiodes. In these devices, the semiconductor material absorbs a photon of light, which excites an electron from the valence band to the conduction band (opposite of photon emission). The photo
5. generated electron leaves behind it a hole, and so each photon generates two charge carriers. The increases the material conductivity so call **photoconductivity** resulting in an increase in the diode current. The diode equation is modified as –

$$I_{diode} = (I_d + I_s)\left(e^{V_q/\eta kT} - 1\right) \qquad \ldots\ 3.2.6$$

where,

I_d is dark current i.e. current that flows when no signal is present. I_s is

photo generated current due to incident optical signal.

Fig. 3.2.1 shows a plot of this equation for varying amounts of incident optical power.

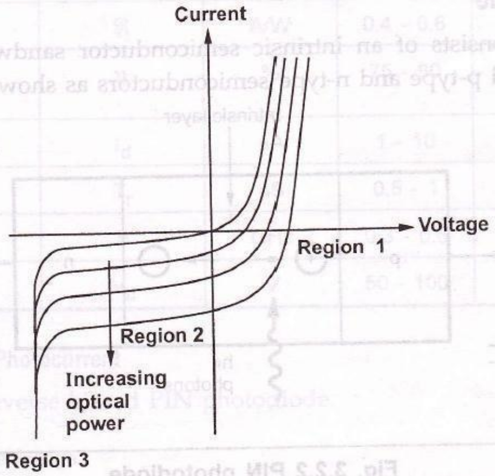


Fig. 3.2.1 V-I characteristics of photodiode

- Three regions can be seen forward bias, reverse bias and avalanche breakdown.

Forward bias, region 1 : A change in incident power causes a change in terminal voltage, it is called as **photovoltaic mode**. If the diode is operated in this mode, the frequency response of the diode is poor and so photovoltaic operation is rarely used in optical links

Reverse bias, region 2 : A change in optical power produces a proportional change in diode current, it is called as **photoconductive mode** of operation which most detectors use. Under these condition, the exponential term in equation 3.2.6 becomes insignificant and the reverse bias current is given by –

$$I_{diode} = (I_d + I_s)$$

- **Responsivity** of photodiode is defined as the change in reverse bias current per unit change in optical powr, and so efficient detectors need large responsivities.

Avalanche breakdown, region 3 : When biased in this region, a photo generated electron-hole pair causes avalanche breakdown, resulting in large diode for a single incident photon. Avalance photodiodes (APDs) operate in this region APDs exhibit carrier multiplication. They are usually very sensitive detectors. Unfortunately V-I characteristic is very steep in this region and so the bias voltage must be tightly controlled to prevent spontaneous breakdown.

PIN Photodiode

- PIN diode consists of an intrinsic semiconductor sandwiched between two heavily doped p-type and n-type semiconductors as shown in Fig. 3.2.2

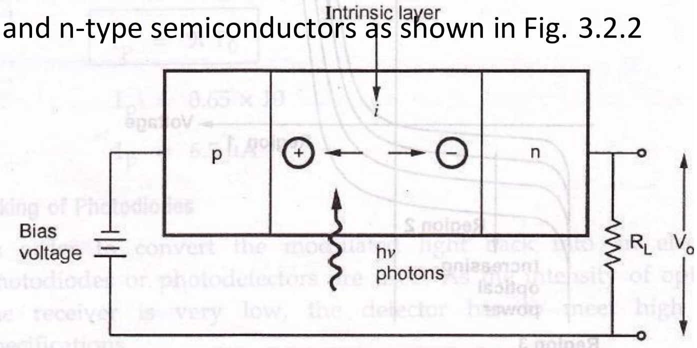


Fig. 3.2.2 PIN photodiode

- Sufficient reverse voltage is applied so as to keep intrinsic region free from carries, so its resistance is high, most of diode voltage appears across it, and the electrical forces are strong within it. The incident photons give up their energy and excite an electron from valance to conduction band. Thus a free electron hole pair is generated, these are

as **photocarriers**. These carriers are collected across the reverse biased junction resulting in rise in current in external circuit called **photocurrent**.

In the absence of light, PIN photodiodes behave electrically just like an ordinary rectifier diode. If forward biased, they conduct large amount of current

PIN detectors can be operated in two modes : **Photovoltaic** and **photoconductive**. In photovoltaic mode, no bias is applied to the detector. In this case the detector works very slow, and output is approximately logarithmic to the input light level. Real world fiber optic receivers never use the photovoltaic mode.

In photoconductive mode, the detector is reverse biased. The output in this case is a current that is very linear with the input light power.

The intrinsic region some what improves the sensitivity of the device. It does not provide internal gain. The combination of different semiconductors operating at different wavelengths allows the selection of material capable of responding to the desired operating wavelength.

Characteristics of common PIN photodiodes

Sr. No.	Parameters	Symbol	Unit	Si	Ge	InGaAs
1.	Wavelength	λ	μ m	0.4 – 1.1	0.8 – 1.8	1.0– 1.7
2.	Reponsivity	$\Re$	A/W	0.4 – 0.6	0.5 – 0.7	0.6– 0.9
3.	Quantum efficiency	H	%	75 -90	50 – 55	60– 70
4.	Darl current	I_d	nA	1 – 10	50 – 500	1 - 20
5.	Rise time	T_r	nS	0.5 – 1	0.1 – 0.5	0.02 – 0.5
6.	Bandwidth	B	GHz	0.3 – 0.6	0.5 – 3	1 – 10
7.	Bias voltage	V_b	V	50 – 100	5 – 10	5 - 6

Depletion Layer Photocurrent

ιϖ) Consider a reverse biased PIN photodiode.

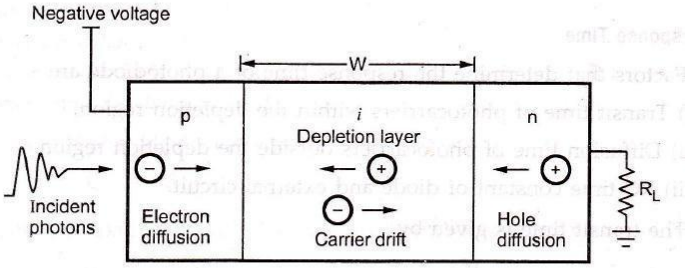


Fig. 3.2.3 Reverse biased PIN diode

- The total current density through depletion layer is –

$$J_{tot} = J_{dr} + J_{diff} \qquad \ldots\ 3.2.7$$

Where,

J_{dr} is drift current densioty due to carriers generated in depletion region.

J_{diff} is diffusion current density due to carriers generated outside depletion region.

- The drift current density is expressed as –

$$J_{dr} = \frac{I_p}{A}$$

$$J_{dr} = q\,\phi_0\,(1 - e^{-\alpha_s w})$$

where,

A is photodiode area.

ϕ_0 is incident photon flux per unit area.

- The diffusion current density is expressed as –

$$J_{diff} = q\,\phi_0\,\frac{\alpha_s L_p}{1+\alpha_s L_p}\,e^{-\alpha_s w} + qP_{n0}\frac{D_p}{L_p} \qquad \ldots\ 3.2.$$

where,

D_p is hole diffusion coefficient

P_n is hole concentration in n-type material.

P_{n0} is equilibrium hole density.

Substituting in equation 3.2.7, total current density through reverse biased depletion layer

is –

$$J_{tot} = q\,\phi_0\left[1 - \frac{e^{-\alpha_s w}}{1+\alpha_s L_p}\right] + qP_{n0}\frac{D_p}{L_p}$$

Response Time

〈 Factors that determine the response time of a photodiode are – Transit

□ time of photocarriers within the depletion region. Diffusion time

□ of photocarriers outside the depletion region. RC time constant

□ of diode and external circuit.

〈 The transit time is given by –

$$t_d = \frac{w}{v_d}$$

ι) The diffusion process is slow and diffusion times are less than carrier drift time. By considering the photodiode response time the effect of diffusion can be calculated. Fig. 3.2.4 shows the response time of photodiode which is not fully depleted.

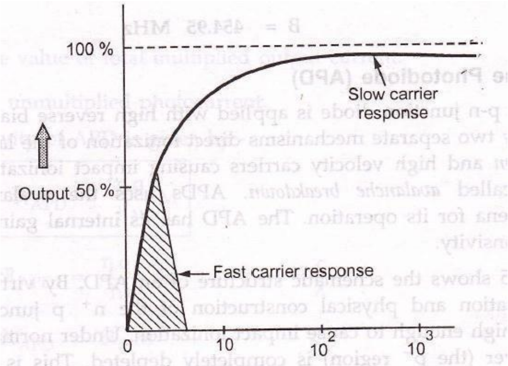


Fig. 3.2.4

- The detector behaves as a simple low pass RC filter having passband of

$$N = \frac{1}{2\pi R_R C_T}$$

where

R_T, is combination input resistance of load and amplifier. C_T is sum of photodiode and amplifier capacitance.

Example 3.2.5 : Compute the bandwidth of a photodetector having parameters as –

Photodiode capacitance = 3 pF

Amplifier capacitance = 4 pF

Load resistance = 50 Ω

Amplifier input resistance = 1 MΩ

Solution : Sum of photodiode and amplifier capacitance

$$C_T = 3 + 4 = 7 \text{ pF}$$

Combination of load resistance and amplifier and input resistance R_T =

$$50\Omega \,||\, 1\text{ M}\Omega \approx 50\ \Omega$$

$$\boxed{\text{Bandwidth of photodetector } B = \frac{1}{2\pi R_R C_T}}$$

$$B = \frac{1}{2\pi\, 50 \times 7 \times 10^{-12}}$$

$$B = 454.95 \text{ MHz}$$ **… Ans.**

Avalanche Photodiode (APD)

- When a p-n junction diode is applied with high reverse bias breakdown can occur by two separate mechanisms direct ionization of the lattice atoms, zener breakdown and high velocity carriers impact ionization of the lattice atoms called avalanche breakdown. APDs uses the avalanche breakdown phenomena for its operation. The APD has its internal gain which increases its responsivity.

  Fig. 3.2.5 shows the schematic structure of an APD. By virtue of the doping concentration and physical construction of the n^+ p junction, the electric filed is high enough to cause impact ionization. Under normal operating bias, the I-layer (the p^- region) is completely depleted. This is known as **reach through** condition, hence APDs are also known as **reach through APD** or **RAPDs**

- Similar to PIN photodiode, light absorption in APDs is most efficient in I-layer. In this region, the E-field separates the carriers and the electrons drift into the avalanche region where carrier multiplication occurs. If the APD is biased close to breakdown, it will result in reverse leakage current. Thus APDs are usually biased just below breakdown, with the bias voltage being tightly controlled.

- The multiplication for all carriers generated in the photodiode is given as –

$$M = \frac{I_M}{I_P} \qquad \ldots$$

where,

I_M = Average value of total multiplied output current. I_P =

Primary unmultiplied photocurrent.

- Responsivity of APD is given by –

$$\boxed{\Re_{APD} = \frac{\eta\, q}{h\, v} M}$$

$$\Re_{APD} = \frac{\eta\, q\, \lambda}{h\, v} M \qquad \because\ v = \frac{c}{\lambda}$$

$$\Re_{APD} = \Re_0\, M \qquad \ldots$$

where, $\Re_0$ = Unity gain responsivity

MSM Photodetector

- Metal-semiconductor-metal (MSM) photodetector uses a sandwiched semiconductor between two metals. The middle semiconductor layer acts as optical absorbing layer. A Schottky barrier is formed at each metal semiconductor interface (junction), which prevents flow of electrons.

- When optical power is incident on it, the electron-hole pairs generated through photo absorption flow towards metal contacts and causes photocurrent.
- MSM photodetectors are manufactured using different combinations of semiconductors such as – GaAs, InGaAs, InP, InAIAs. Each MSM photodetectors had distinct features e.g. responsivity, quantum efficiency, bandwidth etc.

- With InAlAs based MSM photodetector, 92 % quantum efficiency can be obtained at 1.3 µm with low dark current. An inverted MSM photodetector shows high responsivity when illuminated from top.
- A GaAs based device with travelling wave structure gives a bandwidth beyond 500 GHz.

Optical Detector

☐ With a proper sketch briefly explain the structure of PIN diode.

☐ Explain the following term relating to PIN photodiode with proper expressions.

Cut-off wavelength.
Quantum efficiency.
Responsivity.

☐ Explain the structure and principle of working of APD. Deduce
☐ the expression for total current density for APD. How the
☐ response time of APD is estimated?
☐
☐ Give expression for passband of APD detector. Compare the
performance parameters of PIN and APD.

•

UNIT-V

OPTICAL NETWORKS AND DISPERSION COMPENSATION

BASICS

1. Optical fiber is basically a solid glass rod. The diameter of rod is so small that it looks

like a fiber.

2. Optical fiber is a dielectric waveguide. The light travels like an electromagnetic wave inside the waveguide. The dielectric waveguide is different from a metallic waveguide which is used at microwave and millimeter wave frequencies.

3. In a metallic waveguide, there is a complete shielding of electromagnetic radiation but in an optical fiber the electromagnetic radiation is not just confined inside the fiber but also extends outside the fiber.

4. The light gets guided inside the structure, through the basic phenomenon of **total internal reflection**.

5. The optical fiber consists of two concentric cylinders; the inside solid cylinder is called the **core** and the surrounding shell is called the **cladding**. (See Fig 1)

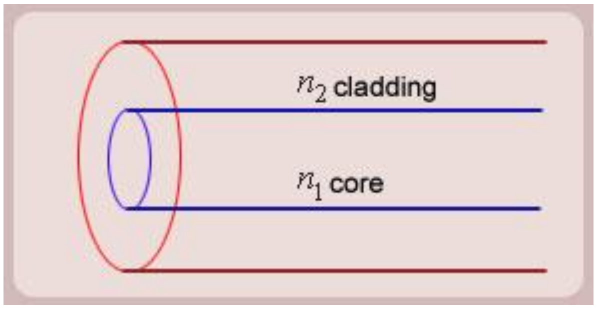


Figure1 Schematic of an optical fiber

6. For the light to propagate inside the fiber through total internal reflections at core-cladding interface, the refractive index of the core must be greater than the refractive index of the cladding. That is $n_1 > n_2$.

1.2 SIMPLE RAY MODEL

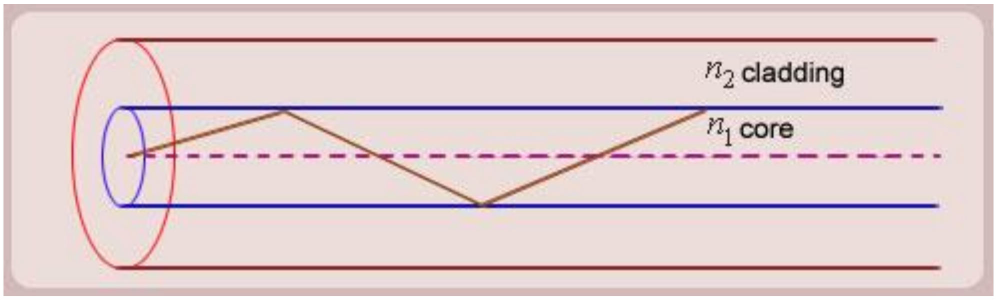


Figure 2 (optical fiber with core, cladding and total internally reflected ray)

For propagation of light inside the core there are two possibilities.

1. A light ray is launched in a plane containing the axis of the fiber. We can then see the light ray after total internal reflection travels in the same plane i.e., the ray is confined to the plane in which it was launched and never leave the plane. In this situation the rays will always cross the axis of the fiber. These are called the **Meridional rays.** (Fig. 2)

2. The other possibility is that the ray is not launched in a plane containing the axis of the fiber.

For example if the ray is launched at some angle such that it does not intersect the axis of the fiber, then after total internal reflection it will go to some other plane. We can see that in this situation the ray will never intersect the axis of the fiber. The ray essentially will spiral around the axis of fiber. These rays are called the **Skew rays.**

So it can be concluded that if the light is to propagate inside an optical fiber it could be through two types of rays

a) Meridional rays: The rays which always pass through the axis of fiber giving high optical intensity at the center of the core of the fiber.

b) Skew Rays: The rays which never intersect the axis of the fiber, giving low optical intensity at the center and high intensity towards the rim of the fiber.

1.3 Propagation of Meridional Rays

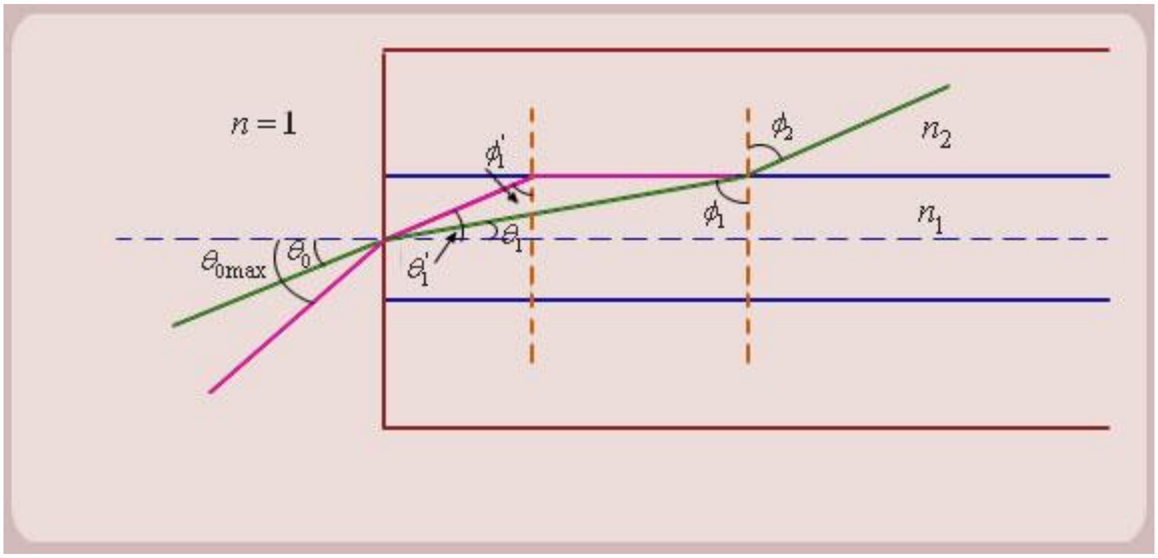


Figure (3)

1. Let us consider figure 3. A ray is launched from outside (air) at an angle θ_0 , from the axis of the fiber.
   The question is, under what conditions the ray is ultimately guided inside the core due to total internal reflections at the core cladding boundary?

2. Let the ray makes an angle θ_1 with the axis of the fiber inside the core, and let the ray make an angle ϕ_1 with core -cladding interface. Let ϕ_2 be the angle of refraction in the cladding.
   If ϕ_1 < critical angle the ray is refracted in cladding. The ray which goes to cladding is lost and is not useful for communication. The ray which is confined to the core is useful for optical communication.

3. Now as we increase the launching angle θ_0, the angle θ_1 also increases.

Since

$$\theta_1 + \phi_1 = \frac{\pi}{2},$$

ϕ_1 decreases and at some point becomes less than the critical angle. When ϕ_1 equals the critical angle, ϕ_2 equals $\pi/2$. The maximum launching angle then corresponds to $\phi_2 = \pi/2$.

4. Let us apply Snell's law at the launching point and at the core-cladding interface for the maximum launching angle $\theta_{0\max}$. For this case let $\theta_1 = \theta_1^{'}$ and $\phi_1 = \phi_1^{'}$

we then have

$n_1 \sin\phi_1' = n_2$ (since $\phi_2' = \frac{\pi}{2}$)

$$\Rightarrow \sin\phi_1' = \frac{n_2}{n_1}$$

now,

$$\sin\theta_{0\max} = n_1 \cos\phi_1^{'} = n_1\sqrt{1-\sin^2\phi_1^{'}}$$
$$= n_1\sqrt{1-\frac{n_2^{\ 2}}{n_1^2}} = \sqrt{n_1^2 - n_2^2}$$

So the sine of the maximum angle at which the ray will be guided inside the fiber is given by square root of the difference of squares of the refractive indices of the core and cladding. The quantity $\sin\theta_{0\max}$ is called the **NUMERICAL APERTURE** of an optical fiber. The NA is a measure of the power launching efficiently of an optical fiber.

5. Numerical Aperture: This parameter tells us that if we take an optical fiber and put it in front of an optical source then how much light is collected by the fiber from the source. Smaller the value of N.A, smaller the value of $\theta_{0\max}$ (maximum launching angle) and smaller is the power accepted by the fiber. In other words, if the light is available from various directions from the source, only a portion of light is accepted by an optical fiber and the remaining part of the light is rejected by it.

6. If we want good light launching efficiency then $\theta_{0\max}$ should be as large as possible. Since $\sin\theta_{0\max}$ is related to the difference of the squares of the refractive indices of the core and the cladding, the difference of squares of the refractive indices should be as large as possible.

So, for good launching efficiency, n_1^2 should be large compared to n_2^2. Since the material for the optical fiber has been chosen as glass, the refractive index of the core is practically fixed to about 1.5.

The only choice therefore we have is to reduce the refractive index of the cladding for good launching efficiency. Since $n_2 = 1$ (i.e., no cladding) is the minimum possible value, it suggests that the cladding is an undesirable feature. In the first look it then appears that the cladding is only for mechanical support.

4. DISPERSION

1. The amount of light accepted by an optical fiber is only one of the parameters in optical communication. A more important parameter is the data rate which the fiber can handle since the primary purpose here is to send information from one point to another.

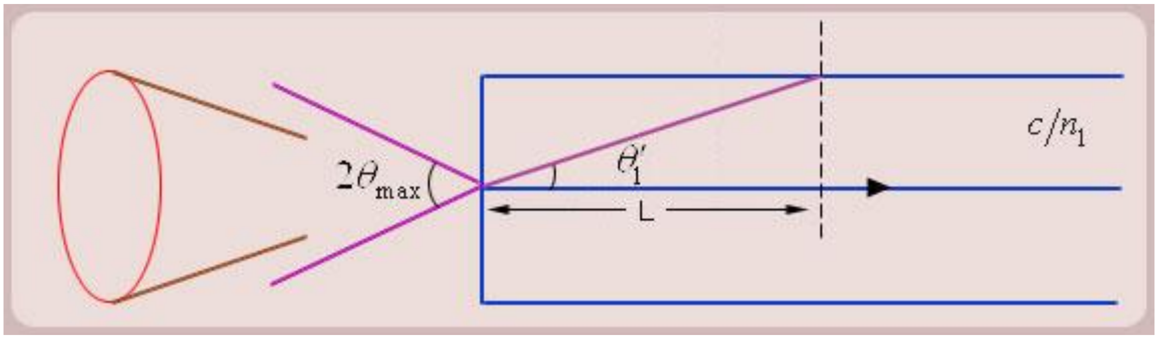


Figure (4)

2. (a) As we see from the figure 4, all the rays contained within the cone $2\theta_{0\max}$ are accepted by the optical fiber.

(b) Let us take two extreme rays; one at the lowest possible angle (along the axis of the fiber), and one at the highest possible angle ($\theta_{0\max}$). Take a length L along the fiber axis traveled by the rays.

(c) Let us now transmit a narrow pulse of light. The light pulse indicates binary information. If there is a pulse then a bit is present, otherwise the bit is absent. When the light is switched on, all the rays are switched on at the same time. The pulse energy is therefore divided between different rays which travel by different paths inside the fiber.

(d) The pulse along the axis of the optical fiber takes less time to travel the distance L, than the pulse which travels at the extreme angle $\theta_{0\max}$.

(e) As shown in the figure 4, the distance traveled by the extreme ray is $\frac{L}{\cos\theta_1'}$.

The time difference between the axial ray and the extreme ray then is:

$$\Delta t = \frac{L}{\cos\theta_1'}\frac{n_1}{c} - \frac{L}{c}n_1$$

$$= \frac{Ln_1}{c}\left(\frac{1}{\cos\theta_1'} - 1\right)$$

$$= \frac{Ln_1}{c}\left(\frac{n_1}{n_2} - 1\right)$$

$$= \frac{Ln_1}{cn_2}\left(n_1 - n_2\right)$$

where c is velocity of light. Since the core material is glass, $n_1 \approx 1.5$, and since $n_2 \leq n_1$, it can lie between 1 and 1.5. The ratio n_1 / n_2 then lies between 1 and 1.5 only. The time difference Δt per unit length therefore is more or less proportional to $\left(n_1 - n_2\right)$.

$$\Delta t \text{ per km} \quad \propto \quad (\; n_1 - n_2 \;)$$

The time difference Δt essentially is the measure of pulse broadening on the optical fiber.

This phenomenon is called **DISPERSION** of an optical fiber. The dispersion (pulse broadening) has to be small since the data rate is inversely proportional to the pulse broadening. For high speed communication (high speed does not refer to the time taken by data to reach the destination but it refers to the number of bits per sec) the pulse broadening and hence the dispersion should be minimal.

(f) For low dispersion ($n_1 - n_2$) should be as small as possible. So for an optical fiber the refractive index of core has to be made as close to the refractive index of cladding as possible.

3. Contradictory Requirement:

(a) For higher launching efficiency (higher NA), $n_1 - n_2$ should be **as large as possible**.

(b) For high data rate (bandwidth), $n_1 - n_2$ should be **as small as possible**.

The two are contradictory requirements.

Since data transfer rate is rather more important in communication, $n_1 - n_2$ is made as small as the fabrication technology permits.

So for all practical fibers, $\frac{n_1 - n_2}{n_1} \approx 10^{-2} - 10^{-3}$

Refractive index of the cladding differs from that of the core by only 0.1 to 1%.

3. Different types of fibers:

1. STEP INDEX FIBER

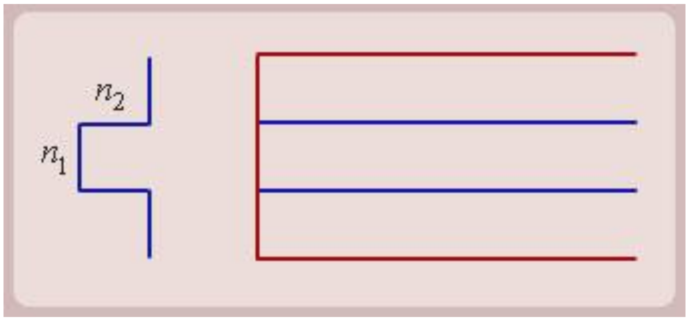


Figure (5): **Step Index Fiber** (Refractive index profile)

For this fiber the refractive index of the core is constant (see Fig 5). Since refractive index profile looks like a pulse or step, this kind of fiber is called the **STEP INDEX FIBER.** This structure is useful for analyzing propagation of light inside an optical fiber. Generally it is not used in practice because data transfer rate in this fiber is the lowest.

Just as a small exercise we can ask, what kind of pulse broadening occurs in a step index fiber if we do not use cladding?

Let us take 1Km of the optical fiber.

Since $n_1 = 1.5, n_2 = 1$ and $L = 1000m$,

$$\Delta t = \frac{L}{c}.\frac{n_1}{n_2}\left(n_1 - n_2\right)$$

$$= \frac{10^3}{3\times10^8}.\frac{1.5}{1}\left(1.5-1\right)$$

$$= .25\times10^{-5}\,\text{sec}$$

$$4\ =$$

$$=$$

Bandwidth $\approx \dfrac{1}{\Delta t} = \dfrac{1}{2.5\times10^{-6}} = 4\times10^5\,Hz$

So if we make a cladding-less optical fiber, its light launching efficiency is excellent but it has hardly any bandwidth. Even an electrical cable is better than the optical fiber.

Important Conclusion: The cladding is an essential part of an optical fiber. It does not just provide the mechanical support but increases the bandwidth of the fiber.

We can observe from the expression for pulse broadening that $\Delta t \propto L$ keeping all other parameters constant.

Since $BW \,\square\, 1/\Delta t$, we get

$$\Rightarrow \text{BW}\times L = const.$$

Important: We can trade in the bandwidth for the length and vice versa. That is, we can send low bit rate signals over long distances and high bit rate signals only over short distances.

2. GRADED INDEX FIBER

(a) In a step index fiber since the refractive index is constant inside the core, the velocity of all the rays is constant and hence there is travel time difference between different rays. If we develop a system where the rays which travel longer distances travel with higher velocities and the rays which travel shorter distances travel with lower velocities, the pulse spread on the fiber can be reduced and consequently the bandwidth can be increased.

(b) The ray which is at a higher angle, should speed up and the ray which is along the axis of the fiber should travel with the slowest possible velocity.

Since velocity is inversely proportional to the refractive index, it can be manipulated by changing the refractive index of the core. The refractive index of outer layers of the core should be smaller compared to that of the inner layers, so the rays that go in the outer layers, travel faster.

So we find that for reducing dispersion, the refractive index at the center should be maximum and it should gradually decrease from the center to the core-cladding interface. The rays that go at higher angles speed up and the dispersion gets reduced. 2

In this fiber we grade the refractive index profile of the core and consequently it is called the **graded index fiber.**

A graded index fiber and the ray propagation is shown in the figure 6:

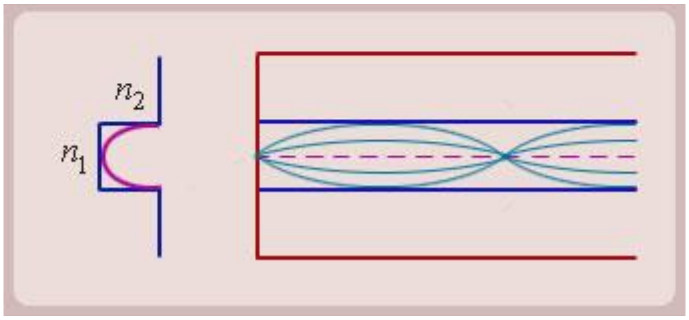


Figure (6): (Graded Index Profile)

(c) If we taper the profile optimally, we get the dispersion reduction compared to that for a step index fiber, even by a factor of thousand. The data rate of a typical graded index fiber is typically 10 to 100 times higher compared to a step index fiber.

Therefore, in practice, even for LANs, we use GIF (Graded Index Fiber) instead of SIF (Step Index Fiber).

3. SINGLE MODE OPTICAL FIBER

The light basically consists of wave fronts. A line perpendicular to a wave front is called the ray. Light is an electromagnetic wave and when we say it travels like a ray it is a collection of wavefronts which move.

Let us take an optical fiber with light rays propagating in it. The rays and the wave fronts which are perpendicular to the rays, are as shown in figure 7:

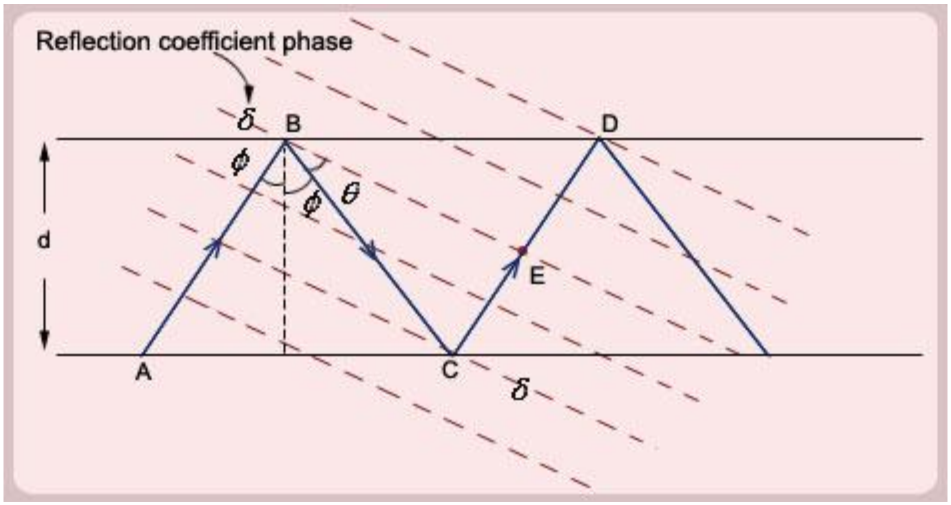


Figure (7): Core of optical fiber, rays with wave fronts

Let us consider a phase front corresponding to the ray AB and passing through the point B. This phase front also meets the ray CD at point E. In other words, the phase of the ray at B (just before the reflection) is same as that of the ray at point E. That is to say that the phase change corresponding to the distance BCE added with the phase (δ) of the reflection coefficient at points B and C should be a multiple of 2π . This is what is called the condition for the constructive interference.

From simple geometric considerations we have

$$\theta + 2\phi = \pi / 2$$
$$BC = d \sec\phi$$
$$\begin{aligned} CE &= BC \sin\theta = d \sec\phi . \sin\left(\pi / 2 - 2\phi\right) \\ &= d \sec\phi \cos 2\phi \end{aligned}$$

phase change from B to E is

$$\begin{aligned} \Phi &= \frac{2\pi}{\lambda} . n_1 (BC + CE) + 2\delta \\ &= \frac{2\pi}{\lambda} n_1 \{ d \sec\phi + d \sec\phi \cos 2\phi \} + 2\delta \end{aligned}$$

For constructive interference the phase change should be multiple of 2π

$$\Rightarrow \Phi = 2m\pi$$

Simplifying equations we get a condition for sustained propagation of light rays inside the core as

$$\frac{2\pi\, n_1\, d \cos\phi}{\lambda} + \delta = m\pi$$

It can be noted that for $\phi = \pi / 2$ (i.e. the ray along the axis of the fiber), $\delta = 0$ and the condition is satisfied with $m = 0$ for any value of n_1, d and λ.

As $\left(n_1 d / \lambda\right)$ increases (either due to increase of the diameter of the core or refractive index of the core, or decrease in wavelength) more values of m satisfy the condition and therefore have sustained propagation inside the fiber.

The above phase condition can be satisfied only by discrete rays entering the structure i.e. rays at finite number of angles are accepted by the optical fiber. The ensemble of rays entering at a specific angle from the axis of the fiber gives discrete optical intensity distributions. These are called the modes of an optical fiber.

From the expression of the phase matching condition we find that as d increases, the number of rays accepted by the optical fiber increases and as d decreases the number of rays decreases.

Since the dispersion is due to presence of multiple rays (modes), if only one ray is made to propagate inside the fiber, there is no dispersion. So if we take a value of d small enough such that it satisfies the phase condition only the lowest value of m, only one mode will propagate inside the fiber.

The lowest value of m corresponds to the ray traveling along the axis of the fiber. In fact this ray does not have any constraint on the size of the fiber etc, as it does not really go through the total internal reflection at the core cladding boundary. This ray therefore always propagates.

The optical fiber in which only one ray travels along the axis of fiber is called the ***single mode optical fiber***.

Single mode optical fiber is the best amongst the three types of fibers, namely the step index fiber, GI fiber and the single mode fiber.

In a long distance communication, we use single mode optical fiber, whereas in LANs we generally use graded index optical fiber.

Note: For single mode optical fiber however we have to use a source like laser because the diameter of the fiber is very small and without a highly collimated beam, sufficient light can not be launched inside the fiber.

The three types of fibers have typical diameters as follows:

OPTICAL FIBERS	**CORE DIAMETER.**
SM	$5-10\mu m$
GRADED INDEX	$50-60\mu m$
STEP INDEX	$50-60\mu m$

Note: The Cladding Diameter for all types of fibers has been standardized to $125\mu m$

Limitations of the Ray-model

(1) The ray model gives an impression that during total internal reflection the energy is confined to the core only. However, it is not so. In reality the optical energy spreads in cladding also.

(2) The ray model does not speak of the discrete field patterns for propagation inside a fiber.

(3) The ray model breaks down when the core size becomes comparable to the wavelength of light. The ray model therefore is not quite justified for a SM fiber.

The limitations of the Ray model are overcome in the wave model discussed in the next module.

g. due to temperature variation, moisture and dust etc.